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# 4-Dimensional Process-Aware Site-Specific Construction Safety Planning

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# 4-Dimensional Process-Aware Site-Specific Construction Safety Planning

**by**

**Sooyoung Choe, B.E.; M.S.E.**

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## 4-Dimensional Process-Aware Site-Specific Construction Safety Planning

Sooyoung Choe, Ph.D.

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The construction industry has one of the worst occupational health and safety records of all industries. In spite of stringent regulations and much attention towards reducing risks in the physical environment, the construction industry continues to be associated with high levels of accidents, injuries, and illnesses. Construction safety management activities are typically categorized into safety planning and execution processes. Despite the interdependent relationship between safety planning and execution processes, current safety planning processes lack a systematic approach because of limited safety tools and site-specific information available. As a result, safety planning and execution processes are generally segregated and, consequently, most safety execution processes rely on ad-hoc safety activities during construction.

The objective of this research is to systematically formalize the construction safety planning process in a 4-dimensional (4D) environment to address site-specific temporal and spatial safety information, by leveraging project schedules and information technology to improve current construction safety management practices. Prior to developing a specific framework, this research presents a safety risk generation and control model to describe the phenomenon of dynamic safety risk, incorporating construction domain knowledge. The proposed model addresses how the inherent risk of

a worker can be transformed by different measurable contexts of activities. Based on the theoretical model, this research assessed safety risk of different construction trades in a quantitative manner. By integrating multiple national injury databases, safety risks of different construction occupations were analyzed to explain common risk types, sources of injury, and risk scenarios associated with each occupation type. With results of safety risk analysis as a reference, a formalized safety planning framework to aid in developing a long-term safety risk prediction plan was proposed. The proposed framework analyzed activity, work period, and work zone safety by integrating a project schedule and a 3D model. The proposed safety planning process was tested in a real-world project.

This research advances safety knowledge, integrating site-specific temporal and spatial information, and significantly affecting the construction safety planning process. The proposed safety planning approach can provide safety personnel with a site-specific proactive safety planning tool that can be used to better manage jobsite safety by predicting activity risk, work period risk, and work zone risk in advance. In addition, visual safety materials can also aid in training workers on safety and, consequently, being able to identify site-specific hazards and respond to them effectively.

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# Chapter 1 Introduction

The construction industry has one of the worst occupational health and safety records of all industries. According to the Bureau of Labor Statistics, in 2013, 828 construction workers were killed, which represents 18.1% of fatal work injuries in the United States (BLS 2013). 828 fatalities indicate that the fatal work injury rate is 9.7 for every 100,000 full-time equivalent construction workers, and United States (US) construction workers are approximately 2.94 times more likely to be killed compared to the average fatal work injury rate for all industries, which is 3.3.

Figure 1 shows the annual fatality and disabling rate for construction industry between 1952 and 2004.

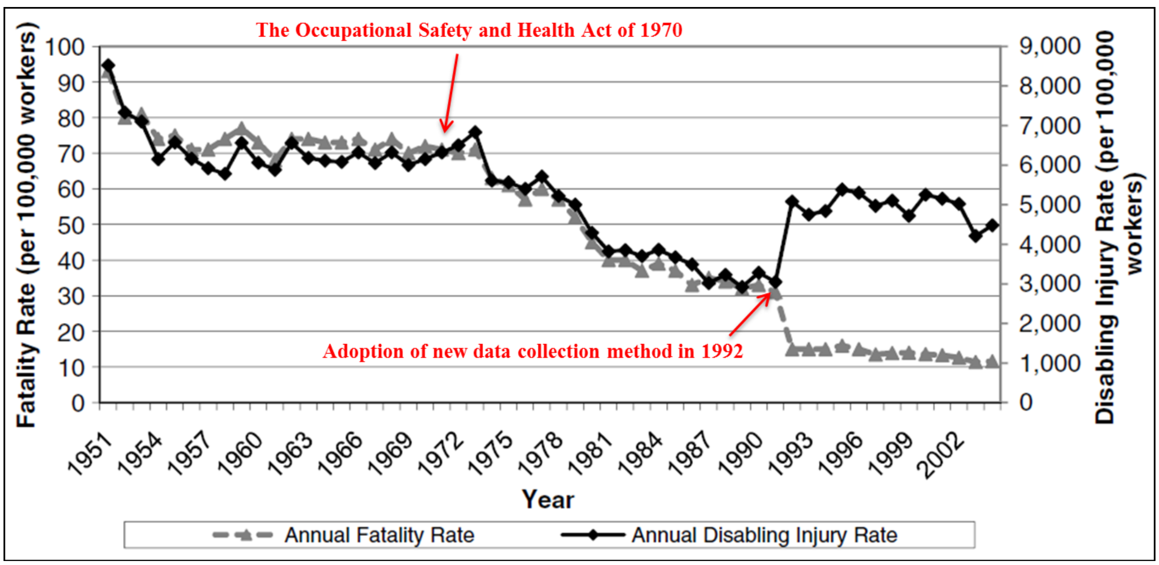



Figure 1: Annual fatality and disabling rate for construction industry between 1952 and 2004 (Esmaeili and Hallowell 2011)

As shown in Figure 1, since the Occupational Safety and Health Act of 1970 was established, which places the responsibility of construction safety on the employer, fatality and disabling rate in the construction industry has dramatically decreased. After this federal law came into effect, various injury prevention strategies have been developed and resulted in a significant improvement of safety management in the construction industry (Esmaeili and Hallowell 2011). However, during the last decade, construction safety improvement has decelerated and fatality rate in the construction industry is still much higher than other industries (BLS 2013). Therefore, innovative injury prevention practices need to be developed to improve current construction safety management practices.

This chapter introduces the importance of safety planning, summarizes current process and challenges of safety management practices, provides the research vision and research questions, and describes the organization and structure of this dissertation.

## 1.1 PROBLEM STATEMENT

In spite of stringent regulations and much attention towards reducing risks in the physical environment, the construction industry continues to be associated with high levels of accidents, injuries and illnesses. The high level of risk in the construction industry has been explained by inherent characteristics of the construction industry. One of unique characteristics is the dynamic nature of the construction work environment. Unlike what happens in other industries having static and indoor work environment, construction sites are very dynamic in terms of ground conditions, temporal structures, weather conditions, and equipment (Fredericks et al. 2005). The coexistence of work teams with different tasks working in a common area increases the complexity of safety risk profiles. Also, the work teams are in constant rotation throughout the project and their members may also change along the way (Carter and Smith 2006; Hinze 1997; Hinze and Wilson 2000; Yi and Langford 2006).

The most effective way for improving safety performance is to prevent accidents before they occur. In this manner, proactive safety management is important. Typical safety planning process includes the following three-steps: hazard identification, risk assessment, and safety control (Tixier et al. 2002). Hallowell and Gambatese (2009) stated typical construction safety practices focus more on hazard identification and risk assessment are typically performed through subjective safety experts' judgement. Due to the lack of tools, frequent and thorough risk analyses at construction sites are hardly ever performed. (Tang et al. 1997). Moreover, hazard identification levels are often far from ideal (Carter and Smith 2006). Also, Rozenfeld et al. (2009) pointed out that risk levels in construction settings fluctuate with dynamic work environment and, thus, uniform levels of investment in proactive safety measures can be illusive and inefficient.

Despite the interdependent relationship between safety planning and execution processes, current safety planning practice lack a systematic approach to effectively identify and manage hazards prior to construction that reflect the dynamic nature of construction. Current safety planning activities lack site-specific information and, when general safety plans are used as safety materials, safety meetings/trainings are less effective and result in workers not being able to identify site-specific hazards and respond to them effectively. Due to ineffective safety planning process, safety planning and execution processes are generally segregated and, consequently, most safety execution processes rely on ad-hoc safety activities during construction. Given that the majority of hazards are generated from specific site conditions and activities in construction work zones, developing site-specific safety plans is fundamental in order to improve the safety execution process and, consequently, site-specific safety management at the jobsite.

## 1.2 MOTIVATING CASE

In order to better understand the current state of practice in construction safety management and further understand the problems related to current safety planning, a case study was conducted on a construction project as a motivating case for this research. The motivating case is a four story parking garage project that is currently under construction in Austin, Texas, and the gross square footage is 1,637,000. The general contractor in this project is recognized as one of the leading companies in terms of safety and innovative solutions in the construction industry. In this project, a safety manager from the general contractor was on the jobsite full time and eight safety managers from subcontractors supported him during site visits. Sources of evidence for this case study included: 1) semi-structured face-to-face interviews with the project manager, safety manager, and virtual design coordinator, 2) safety documents review such as preconstruction and pre-task safety plans, and 3) participation in weekly safety meetings on the jobsite for two months.

### 1.2.1 Safety management process

Construction safety management activities are typically categorized into safety planning and execution processes. The main tasks of safety planning include hazard identification, risk assessment, and preparing safety controls based on regulations, company safety policy, and previous experience. The safety execution process includes safety meetings/training and safety inspections during construction. Figure 2 illustrates the state-of-practice in construction safety management process.

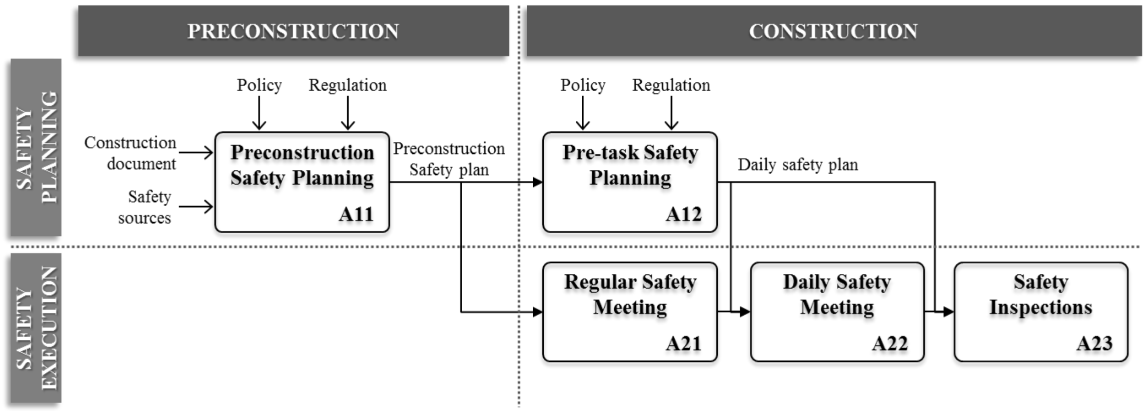



Figure 2: Sate-of-practice safety management process

During preconstruction safety planning (A11 in Figure 2), the safety manager generated a preconstruction safety plan to establish a comprehensive safety program, which was used during construction. The preconstruction safety plan includes jobsite hazard identification and safety execution plans generated from subcontractors. According to the safety manager, he never performed risk assessment since there are no reliable tools. The main sources of this safety plan were construction documents, safety specifications, regulations, a project schedule, and most importantly previous experience of the safety manager. Even though a project schedule was reviewed for preconstruction safety planning, the safety manager mentioned that safety plan and schedule integration is challenging because the project schedule frequently changes. Also, in spite of the fact that this company extensively uses building information modeling (BIM) for scheduling and 4D simulation, as well as design coordination, no BIM techniques were used for safety and the safety planning process relied significantly on traditional 2D drawings, paper-based resources, and previous experience of the safety manager. With the preconstruction safety plan, initial safety meeting was held before construction to review all safety plans with all employees and subcontractors. The safety plan generated in this phase is a basic safety source of pre-task safety planning (A12) and regular safety meetings (A21).

During construction, the safety manager hosted weekly safety meetings (A21), and all project participants were required to attend this meeting every Tuesday on the jobsite prior to work. This safety meeting started with a general safety talk, and weekly work plan and related safety issues were addressed by the general contractor to cover a ballpark of the project and safety plans. After that, daily work plans were addressed by each subcontractor and wrapped up with an informal safety conversation for the specific jobsite safety improvements by field workers. The pre-task meeting (A22) was hosted by each subcontractor using a check-list based pre-task plan (A12) provided from the safety manager. This pre-task meeting covers daily work processes and related safety topics without interference of the general contractor. Results of this meeting were submitted to the general contractor's safety manager on a daily basis. The safety training was only performed with new employees to educate them regarding safety policies and related regulations. Lastly, jobsite safety inspections (A23) were conducted by safety managers as well as all members of the general contractor to prevent dangerous situations in the jobsite. Any hazards identified by members were easily reported to a cloud-based tool using their smart phones and, thus, all project participants could share information.

In this motivating case, safety execution, including safety inspection, was well-organized and performed intensively. However, since the pre-construction safety plan only addressed generic hazard types, it was not effectively used for safety execution practices. In addition, although the safety manager in this project recognized the significance of the relationship between project schedule and safety issues such as dangers of concurrent activities, it was not effectively communicated among project participants. Lastly, although the safety manager agreed that possible positive impacts of integrated safety program with BIM such as early identification of preventable hazards, safety managers did not attend weekly BIM coordination meetings, except for in special circumstances, such as a tower crane erection or dismantlement process.

### 1.2.2 Challenges of state-of-practice safety management

Based on findings from the motivating case study, specific challenges related to construction safety management process are shown in Figure 3 and three main research challenges are summarized subsequently.

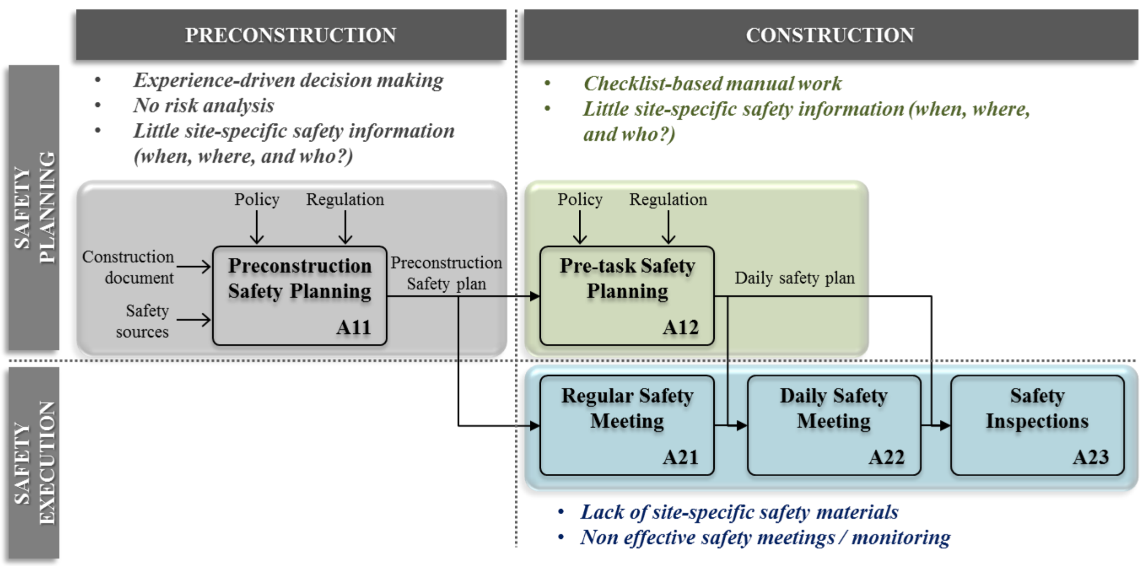



Figure 3: Challenges of construction safety management process

Current safety planning activities lack site-specific information and, when general safety plans are used as safety materials, safety meetings/trainings are less effective and result in workers not being able to identify site specific hazards and respond to them effectively. Due to ineffective safety planning process, safety planning and execution processes are generally segregated and, consequently, most safety execution processes rely on ad-hoc safety activities during construction. Given that the majority of hazards are generated from specific-site conditions and activities in construction work zones, developing site-specific safety plans is fundamental in order to improve the safety execution process and, consequently, site specific safety management at the jobsite. Specific challenges related to construction safety management process are:

- *Lack of systematic safety planning method*

  Current safety planning practice lacks a systematic approach to effectively identify and manage hazards prior to construction to reflect the dynamic nature of construction. Although the other project core values such as quality, time, and cost have been analyzed in systematic ways with numerous reliable national references, safety which is often referred as the most important value, still depends on previous experience of certified safety managers. Although tacit knowledge is recognized as the most valuable type of knowledge in the construction industry (Fischer, 2006), the quality of experience-driven safety planning is often highly dependent on the capability of safety managers and not formalized, and thus, safety knowledge is less effectively shared and communicated among other project participants. Due to the lack of systematic safety planning approach, current hazard identification and risk assessment processes are often too general or not conducted.

- *Lack of site-specific safety information integration*

  Even though the significance of site-specific safety planning development is well recognized, the current safety planning approach does not address site-specific temporal (e.g. when and who will be exposed to potential hazards) and spatial (e.g. location of dangerous zone) information. When general safety plans are used as safety materials, safety meetings/trainings and inspections are less effective and result in workers not being able to identify site specific hazards and respond to them effectively. Due to ineffective safety planning process, safety planning and execution processes are generally segregated and, consequently, most safety execution processes rely on ad-hoc safety activities during construction. Given that the majority of hazards are generated from specific-site conditions and activities in construction work zones, developing site-specific safety plans is fundamental in order to improve the safety execution process and, consequently, site specific safety management at the jobsite.

- *Lack of information technology use*

  Another challenge of current safety planning process is lack of safety resources utilized. While information technology-based approaches, such as Building Information Modeling (BIM), have been widely used for project planning and progress monitoring, construction safety planning is still highly dependent on traditional sources such as 2D drawings, paper-based regulations, and tacit knowledge. The motivating case illustrates a real-world project which is consistent with the construction industry as a whole in which BIM is not yet widely used for construction safety planning. Even though the company extensively uses BIM for scheduling and 4D simulation, as well as design coordination through weekly BIM coordination meetings, construction safety still relies on traditional 2D drawings and paper-based sources. As a result, current safety planning approach limits the capability to identify and analyze hazards prior to construction and has the potential to be improved with the integration of information technology.

### 1.3 RESEARCH VISION AND RESEARCH QUESTIONS

I envision that the construction safety planning process can be systematically formalized through a 4-dimensional (4D) environment, which integrates 3D and time, to address site-specific temporal and spatial safety information. The proposed safety planning approach includes: (1) understanding of generic patterns of risk generation and mitigation in the dynamic construction work environment, (2) safety risk quantification, and (3) site-specific temporal and spatial information integration. Figure 4 illustrates an overview of the proposed research.

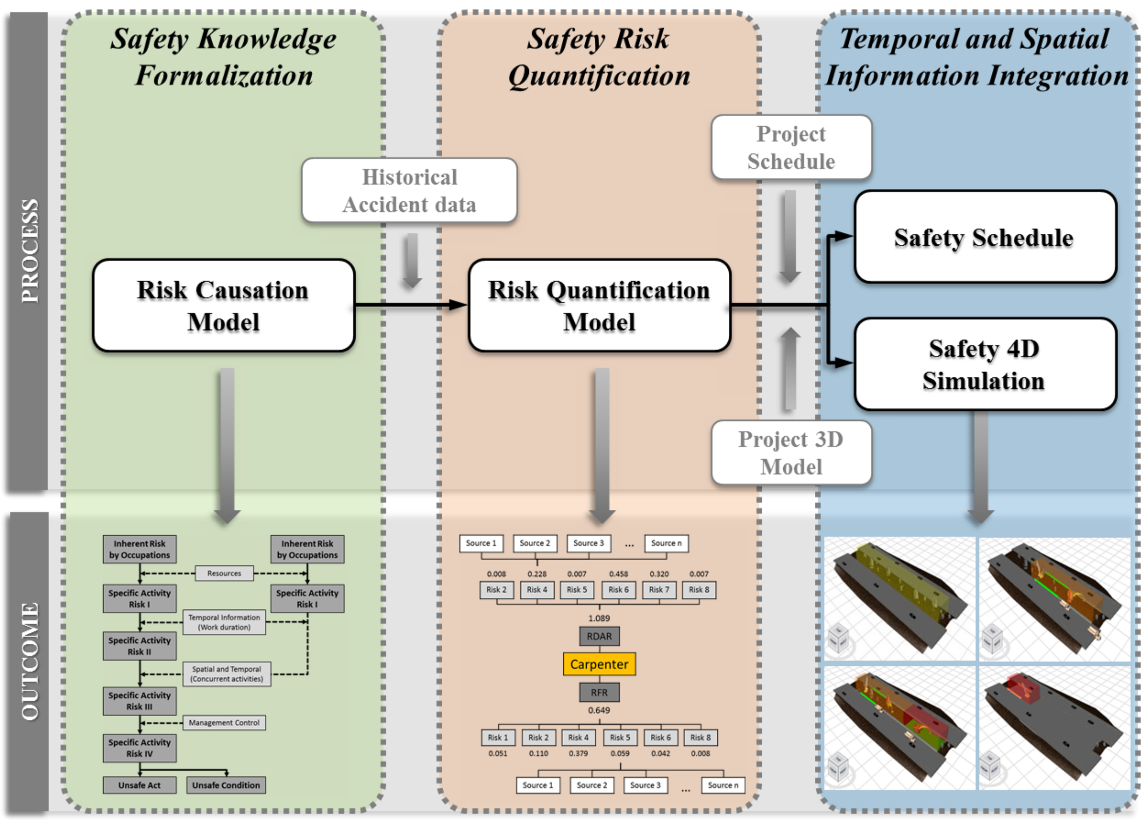



Figure 4: Overview of the proposed research

I envision that safety personnel can analyze activity safety risk and prepare proper responses in the early stage of the project based on historical accidents data and general project information. The results of activity risk analysis can be integrated with a project schedule to incorporate safety knowledge and site-specific temporal information. The proposed temporal information integration process will allow identifying and prioritizing work period risk with baseline activity risk data. The safety schedule will be integrated with a project 3D model (i.e. BIM) in order to extract site-specific spatial information. Safety 4D simulation, which integrates activity risk data, site-specific temporal and spatial information, can allow safety personnel to identify concurrent activities as well as analyze dangerous zones in a specific time period. In addition, this visualized safety 4D simulation can be used for safety training.

Even though all safety practices are important and interrelated, I focused on improving the macro level of construction planning process, given that subsequent safety practices can be significantly impacted by macro level plans. This proposed framework will automatically address dynamic updates of construction document, especially project schedules, rather than dynamic changes of micro level work situations such as uncertainties of workers, logistics, weather, or activity delays which are not updated in a project schedule or 3D model. These kinds of micro level uncertainties should be considered during construction and may be integrated with the proposed macro level safety planning process. In addition, the proposed safety framework identifies risky activity, risky work periods, and risky work zones to aid safety personnel in preparing risk controls in advance more effectively. Therefore, specific safety controls are not integrated with the proposed framework.

The following research questions have been developed in support of the aforementioned research vision.

**Question 1. How can worker safety risk be transformed in a dynamic construction work environment?**

- Question 1.1 How can a generic pattern of risk transformation be explained in a dynamic construction work environment?
- Question 1.2 What are the measurable factors (inputs) to analyze dynamic safety risk (outputs) of a worker?

The first research question addresses the knowledge formalization aspect of this research. The answer to this question will help understand how the safety risk of a worker can be transformed in dynamic construction work environment. A risk generation and mitigation model was developed as a result. Detailed discussions related to research question 1 can be found in Chapter 2.

**Question 2. How can a worker's safety risk be predicted in a quantitative manner?**

- Question 2.1 How can inherent safety risk of a worker be quantified by occupation types?
- Question 2.2 How can inherent risk of a worker be decomposed to explain why an occupation type is dangerous?

The second research question addresses the safety risk quantification aspect of this research based on the model developed in the first research question. The answer to this question will provide a reference of safety risk analysis by explaining how much and why a specific occupation type is dangerous. Detailed information related to research question 2 can be found in Chapter 3.

**Question 3. How can safety risk of multiple activities be analyzed with integrated site-specific temporal and spatial information?**

- Question 3.1 How can activity risk, work period risk, and work zone risk be predicted?
- Question 3.2 How can safety risk data be automatically updated as a schedule and 3D model is updated?

The third research question addresses the temporal and spatial information integration aspect of this research. The answer to this question will provide practical application of results of research question 2 by explaining when and where a project will encounter dangerous situations. The results of research question 3 are shown in Chapter 4.

### 1.4 READER'S GUIDE TO THE DISSERTATION

This PhD dissertation is structured into five chapters. Chapter 1 presents the introduction, motivating case with challenges, research vision and three research questions. Chapters 2, 3, and 4 address Research Questions 1, 2, and 3, respectively, with each of these chapters written as stand-alone documents that contain an introduction, literature review, research method, results, and conclusions sections. Chapter 5 summarizes the dissertation's conclusions and findings as well as future research.

# Chapter 2 Transforming Inherent Risk in the Construction Industry: A Risk Generation and Control Model

This chapter presents a risk generation and control model to describe the phenomenon of dynamic safety risk with construction domain knowledge. Based on extensive literature review and analysis of fatality reports, the proposed model addresses how the inherent risk of a worker can be transformed by different measurable risk factors such as activity resource and temporal and spatial risk factors, as well as management control. Successful implementation of the proposed model is expected to improve the understanding of safety risk and provide a theoretical basis for the development of practical risk analysis methods in the construction industry.

## 2.1 INTRODUCTION

In order to improve occupational safety and health, numerous studies have been conducted which can be classified into three main areas: accident analysis, risk analysis, and accident/risk intervention (Sousa et al. 2014). According to the Merriam-Webster Dictionary, accident is defined as 'a sudden event (such as a crash) that is not planned or intended and that causes damage or injury (Accident 2015). Risk is defined as 'the probability that something bad or unpleasant (such as an injury or a loss) will happen' (Risk 2015). As seen in the definitions, the main difference between the two terms is timing of events. Therefore, accident analysis approaches examine problems that have already occurred, while risk assessment approaches study problems of future events. Regardless of the two different approaches, causal factors of accidents and risk should be identified to understand problems of accidents and risk. However, due to the nature of different timing of events, available sources are different for the two approaches. Accident analysis attempts to explain how and why accidents happened with causal factors such as unsafe conditions, unsafe acts, or/and management failures. These factors are measurable at the time of accident analysis because undesired events already happened. However, most factors used for accident analysis, such as unsafe acts, cannot be measured at the time of risk analysis, which needs to be conducted prior to project/activity. Therefore, risks analysis requires different measurable sources at the time of analysis to identify and evaluate potential undesired events.

A number of accident causation models have been developed to explain how and why accidents occurred. An accident causation model is a conceptual representation of accident causation, which typically explains the relationship between causes and effects (Qureshi 2007). Based on theoretical background from the models, various practical accident investigation methods have been developed. Also, specific accident models and methods in the construction industry were developed to reflect unique characteristics of the construction domain. On the other hand, many risk analysis methods have been developed to predict possible undesired events and mitigate them, but the area of risk analysis lack systematic theoretical models to explain the phenomenon of safety risk causation, especially in the construction domain.

This study proposes a systematic risk generation and control model of the construction industry, which explains patterns of risk generation with measurable factors at the time of risk analysis. The proposed model addresses how inherent risk of an occupation can be transformed by different measurable risk factors such as activity resource and temporal and spatial risk factors as well as management control. The objectives of the model are to improve the understanding of safety risk and provide a theoretical background for risk analysis in the construction industry.

## 2.2 BACKGROUND RESEARCH

A large number of occupational safety and health studies related to accident and risk analysis were reviewed. In order to develop a new risk generation and control model, previous studies related to accident causation models and accident analysis methods, and risk assessment methods are discussed.

### 2.2.1 General Accident Causation Models

An accident causation model is a simplified representation of accidents with the identification of critical causal factors and relationship among them to aid in preventing future reoccurrence (Qureshi 2007). There are many models describing causation of accident and they are generally classified into four categories: sequential, epidemiological, systemic, and human error models.

Sequential accident models were relatively early attempts to describe industrial accidents. Heinrich's domino model (Heinrich et al. 1950), first introduced in the late 1920s, stated accidents as result from a chain of sequential events, metaphorically like a line of dominoes falling over. In Heinrich's domino model, removal of a key event such as an unsafe act or unsafe condition prevents the start of the following events such as injury. Bird (1984) updated the domino sequence to reflect management's relationship with the causes and effects of all incidents. Numerous accident analysis and risk assessment methods such as Failure Modes and Effects Analysis, Fault Tree Analysis, Event Tree Analysis, and Cause-Consequence Analysis are based on sequential accident models. Even though sequential accident models gained popularity and were the foundation for many advanced models, they were criticized because sequential accident models assumed the cause-effect relation between consecutive events to be linear and deterministic (Abraha and Liyanage 2015).

Epidemiological accident models viewed that multiple factors might play a role in accident causation. Gordon (1949) paralleled accidents to diseases. He classified factors influencing accidents into the host (accident victim), agent (deliverer of the injury), and environment (the accident setting). The energy model, first introduced by Gibson (1961) and later developed by Haddon (1968), proposed that accidents are caused by undesired transfers of various types of energy which influence existing barriers. The Swiss Cheese Model viewed accidents as a combination of 'latent' and 'active' failures within a system (Reason 1990; Reason 1997). Reason highlighted the pathway from latent, organizational failures (e.g. poor design or planning decisions), to the conditions where active failures (workplace errors and violations) can occur. Despite the better representation of the influence of multiple factors on accident causation, epidemiological accident models made it difficult to explain accidents in complex socio-technology systems (Hollnagel 2004; Rasmussen 1997).

More recent accident causation models, such as systemic accident models, emphasize a holistic approach towards the understanding of accidents in complex socio-technology systems. Systemic accident models view accidents as outcomes of complex and dynamic interactions between system components such as human, technical, and environment while sequential/epidemiological accident models described accidents as a linear and simple cause-effect relation of events or factors (Hollnagel 2004). Rasmussen (1997) introduced a hierarchical socio-technical framework for modeling the organizational, management, and operational structures that create the preconditions for risk/accidents. AcciMap (Rasmussen 1997; Rasmussen and Suedung 2000) and Systems Theoretic Accident Model and Processes (STAMP) (Leveson 2004) are representative accident analysis methods based on systemic accident models.

In any accident causation model, human error is one of the major causes which leads to accidents, and a number of accident causation models focus on human behaviors and factors. Human error models are mostly based on the accident proneness theory (Greenwood and Woods 1919), indicating that individuals have specific characteristics which make them more or less susceptible to being involved in an accident, and later developed with additional contributory factors which led to human unsafe behavior. Goals Freedom Alertness theory (Kerr 1957), the Human-error causation model (Petersen 1984), the McClay model (McClay 1989) and the Dejoy model (DeJoy 1990) are examples of human error models.

General accident causation models provide a broad perspective of accident processes by representing, classifying, and organizing large amounts of general safety-related knowledge. They explain why and how accidents occur, and a large number of accident/risk analysis methods have been developed based on one or multiple models. However, general accident causation models lack domain specific knowledge. Hence, several construction specific accident causation models have been developed.

### 2.2.2 Accident Causation Models in Construction

Relatively recently, several accident causation models in the construction industry have been developed to include construction specific knowledge. The Distraction model, developed by Hinze (1997), explained that the risk of an accident is generated by a worker's distraction caused by either jobsite hazards or mental worries. This model described the interrelationships between probability of injury occurrence, efficiency of work accomplishment, and mental distraction experienced by the worker. Abdelhamid and Everett (2000) proposed the Accident Root Causes Tracing Model (ARCTM) to support accident investigation methods with three root causes: (1) failing to identify an unsafe condition that existed before an activity was started or that developed after an activity was started; (2) deciding to proceed with a work activity after the worker identifies an existing unsafe condition; and (3) deciding to act unsafely regardless of initial conditions of the work environment. Suraji et al. (2001) developed the Constraint-Response model, and classified the causes of accidents into proximal and distal factors. According to the model, distal factors (project conditions or management decisions) cause responses that generate proximal factors (unsafe condition or act) that lead to accidents. Haslam et al. (2005) perceived an accident mechanism with three hierarchical tiers, which are originating influences (client requirements, project management, or safety culture), shaping factors (worker's attitude or site constraints), and immediate accident circumstances (condition of equipment or communication). Based on Rasmussen (1997), Mitropoulos et al. (2005) developed a systemic accident causation model with construction domain knowledge by emphasizing how production system factors affect the likelihood of risk/accidents during a construction operation. Later, Mitropoulos et al. (2009) proposed the task demand-capability model for construction safety. The model explained the likelihood of risk/accidents increasing as task demands increase, and reducing as applied capabilities increase. All accident causation models introduced provide a comprehensive perspective of accident causation in different mechanisms. Causal factors identified by previous models are mostly classified into unsafe acts, conditions, or/and management failures. Therefore, they are useful to provide frameworks for accident investigation methods, but these accident causation models might be difficult to support risk analysis methods, which require different measurable factors at the time of analysis.

### 2.2.3 Risk Assessment in Construction

In addition to attempts of developing accident causation models, a number of risk assessment methods have been developed using different factors. Everett (1999) quantified ergonomic risks by surveying seven risk factors with safety experts. Jannadi and Almishari (2003) developed the Risk Assessor Model (RAM) to estimate activity risk using a function of severity, probability, and exposure. Lee and Halpin (2003) identified three risk factors and estimated risk of activities associated with utility-trenching process. Baradan and Usmen (2006) compared relative risks of different construction trades using historical fatality and non-fatal injury rates. Yi and Langford (2006) quantified activity risk associated with fall hazards considering several risk factors identified from historical fatality reports in South Korea. Wang et al. (2006) proposed a simulation-based risk assessment model, SimSAFE, to evaluate risk of activities with consideration of likelihood associated with causes of accidents based on historical accident data. Rozenfeld et al. (2010) proposed the Construction Job Safety Analysis (CJSA) to estimate risk of loss of control events identified by safety experts. In addition, several researchers applied the analytic hierarchy process (AHP) to prioritize safety risk factors they identified (Aminbakhsh et al. 2013; Badri et al. 2012; Sun et al. 2008). All risk analysis methods introduced above contributed to the identification of the relationship between specific risk factors and safety performance in different ways, but their methods fail to represent a comprehensive view of risk problems due to the lack of theoretical background and limited number of factors analyzed.

Some researchers attempted to develop risk assessment methods based on previous or their own risk causation models. Hallowell and Gambatese (2007) proposed the Safety Equilibrium Model to describe the mechanism of safety risk created from construction activity and safety risk mitigation generated from safety program elements.

Based on the model, Hallowell and Gambatese (2009) quantified risk associated with tasks in formwork activity using the Delphi method. Although this risk assessment method is based on a theoretical background, the Safety Equilibrium Model did not represent a comprehensive process of risk generation with a comprehensive list of factors and, thus, the risk assessment method fail to fully explain why certain activities are dangerous. Based on the model developed by Mitropoulos et al. (2009), Mitropoulos and Namboodiri (2010) introduced an observational method providing an objective assessment of an activity's task demand based on observable risk factors and production variables. However, as Esmaeili et al. (2015a) mentioned, the method requires identifying relevant factors and their relationships among them for each task. Esmaeili et al. (2015b) proposed an attribute-based risk analysis method inspired by the Human Genome Project which describes limited number of genes can explain vulnerability towards specific kind of diseases. Based on the theoretical background, Esmaeili et al. (2015b) identified and quantified limited number of primary and secondary measurable attributes of struck-by accidents. This attribute-based risk assessment model enables one to address the dynamic nature of a construction activity with safety attributes being selected by users depending on the work environment of an activity. However, the Human Genome Project is not a model to describe the phenomenon of risk or accidents. In addition, their risk analysis method assumed the risks of attributes are static and limited to struck-by accidents only.

The extensive literature reveals that accident causation models in the construction industry comprehensively describe accidents with well-defined factors. As a result, these models enable the support of accident investigation methods, but fail to provide a theoretical background for risk assessment methods, which require understanding of risk development based on measurable factors at the time of risk analysis. In addition, even though a number of risk assessment methods have been developed with construction domain knowledge, they failed to represent a comprehensive view of risk problems due to the lack of theoretical background and limited number of factors analyzed. Therefore, there is a need to develop a comprehensive model which enables a better understanding of the phenomenon of dynamic safety risk with sufficient construction domain knowledge.

## 2.3 Research Method

In order to understand how and why risk is generated, this study examined 32 fatality reports obtained from the National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment Control and Evaluation (FACE) program. Even though the NIOSH investigators identified causes of accidents in reports such as unsafe acts and conditions, the authors focused on identifying patterns of risk generation based on measurable factors for the purpose of risk analysis. Out of 32 cases, 24 (75%) were used for training and eight (25%) were used for testing.

### 2.3.1 Patterns of Risk Generation

The principle of the proposed risk generation model is with the underlying assumption that every worker has an inherent risk. The extent and types of inherent risk varies depending upon his/her occupation type which determines a large number of risk factors. For example, a roofer might have high risk related to fall from roofs because of the nature of work location. On the other hand, a concrete worker might have relatively high risk of being struck by a vehicle such as a backing cement mixer due to the nature of working with construction equipment.  Therefore, it is important to understand that different occupations perform fundamentally different types of work and have different exposure to risk types and factors.

A worker performing a particular activity may be prone to a certain level of risk. There are a number of risks present in activity. These risks in an activity typically vary depending on resources, such as materials and tools, to perform the activity. For example, there may be different levels of risks when a carpenter performs the same elevated work using different tools such as a ladder versus scaffolding. Therefore, inherent risk of an occupation can vary by types of resources to perform a particular activity.

Unlike what happens in other activities having static and indoor work environment, construction activities are highly influenced by temporal and spatial contexts of a jobsite. An activity risk will vary by work duration since work duration typically determines the extent of exposure to risk. An activity risk will vary by work location although the crews are working with the same resources such as pouring concrete on the ground or on the top floor. Also, the level of risk associated with an activity can differ by existence of concurrent activities. For example, pouring concrete activity may be performed early in the morning without any other activities, but it may also be performed at peak times, with several concurrent activities. Therefore, it is important to understand safety impacts of concurrent activities, which can be determined by temporal and spatial contexts of a project.

Activity risk explains how inherent safety risk of an occupation can be changed by resources utilized, as well as temporal and spatial contexts of a project. In order to mitigate expected risk, a construction project typically has safety management practices, such as safety trainings and safety inspections on the jobsite. While activity risk explains a generation aspect of safety risk, safety management explains a control aspect of safety risk. For example, the level of risk using a ladder by a carpenter can be reduced with training on proper use of ladders prior to an activity. Also, level of risk of pouring concrete activity and nearby activities can be minimized by placing a spotter or reinforcing safety inspections on the area of the activities even though these activities are inevitably scheduled at the same time and same location.

Even though management control is well established and implemented, there is always a chance of residual safety risk because all unsafe conditions and unsafe acts cannot be predicted and mitigated by safety controls. These uncontrolled remaining risks may potentially lead to accidents and injuries to workers. However, understanding the mechanism of risk generation and proper management control can minimize the extent of risk and consequently, the probability of undesired events could be minimized.

### 2.3.2 Measurable Risk Factors

The previous section explains the general pattern of risk generation in the construction industry. In order to support risk assessment methods, identification of measurable factors of each category is necessary for better understanding.

Prior to identifying a number of measurable factors (causes), a list of common risk types (effects) was identified. Different construction occupations are exposed to different types of risk. Therefore, understanding common risk types is important for the development of practical risk assessment methods. Based on the Occupational Injury and Illness Classification System (OIICS), seven high level risk types are shown in Table 1. Definitions and detailed risk types can be found at 'Events or Exposure' in the OIICS.

Table 1: Risk Types

| Code | Risk types |
|---|---|
| R1 | Violence and other injuries by persons or animals |
| R2 | Transportation incidents |
| R3 | Fires and explosions |
| R4 | Falls, slips, trips |
| R5 | Exposure to harmful substances or environments |
| R6 | Contact with objects and equipment |
| R7 | Overexertion and bodily reaction |

Source: Occupational Injury and Illness Classification System (OIICS)

As described in the section 2.3.1, risk of a worker varies by resources the worker uses and work conditions in an activity. In addition, these activity resources typically determine risk types workers will be exposed to. For example, a carpenter working with a ladder has a high probability of being exposed to 'Falls, slips, trips' (R4) risk. Table 2 summarizes eight common activity risk factors based on the SIICS. Definitions and detailed activity risk factors can be found at 'Sources of Injury' in the SIICS.

Table 2: Activity Risk Factors

| Code | Activity risk factors |
|---|---|
| ARF1 | Chemicals and chemical products |
| ARF2 | Containers, furniture and fixtures |
| ARF3 | Machinery |
| ARF4 | Parts and materials |
| ARF5 | Persons, plants, animals, and minerals |
| ARF6 | Tools, instruments, and equipment |
| ARF7 | Vehicles |
| ARF8 | Other sources |

Source: Occupational Injury and Illness Classification System (OIICS)

Due to the dynamic nature of work environment in Construction, temporal and spatial contexts highly influence an activity's risk. As Jannadi and Almishari (2003) introduced, the amount of exposure to risk is an important factor typically determined by work duration. Also, from the analysis of fatality reports, time of work and work location play significant roles to determine the type and amount of risk in a seemingly identical activity performed with the same resources. Lastly, as Hallowell et al. (2011) emphasized, construction activities are often influenced by risk caused by nearby activities. Therefore, it is important to analyze safety impacts of concurrent activities which are determined by a project's temporal and spatial information. Table 3 summarizes four temporal and spatial risk factors.

Table 3: Temporal and Spatial Risk Factors

| Code | Temporal and spatial risk factors |
|---|---|
| TSRF1 | Work duration |
| TSRF2 | Time of work |
| TSRF3 | Work location |
| TSRF4 | Concurrent activities |

Most accident causation models as well as risk assessment methods addressed safety management practices playing an important role in reducing risk/accidents. While activity risk factors and temporal and spatial risk factors influence the generation aspect of safety risk, safety management controls influence the mitigation aspect of safety risk. Rajendran and Gambatese (2009) found more than 300 safety management strategies in the construction industry. Since it is impractical including all safety management strategies, this study adapted nine fundamental strategies (SMC1 – 9) identified by Hinze (2002) and two additional controls (SMC10 – 11) identified from the analysis of fatality reports as shown in Table 4.

Table 4: Safety Management Controls

| Code | Safety management controls |
|---|---|
| SMC1 | Demonstrated management commitment |
| SMC2 | Staffing for safety |
| SMC3 | Pre-project and pre-task planning |
| SMC4 | Safety education and training |
| SMC5 | Employment involvement |
| SMC6 | Safety recognition and rewards |
| SMC7 | Accident/incident investigations |
| SMC8 | Drug testing |
| SMC9 | Subcontractor management |
| SMC10 | Safety protection system |
| SMC11 | Others |

### 3.4 Proposed Risk Causation Model

In the section 2.3, a general pattern of risk generation and mitigation was explained with three types of measurable contexts related to a construction project. Based on these findings, the complete risk generation and control model is proposed in Figure 5 to illustrate the safety risk transformation process – from inherent risk to undesired events, with specific factors related to available information.

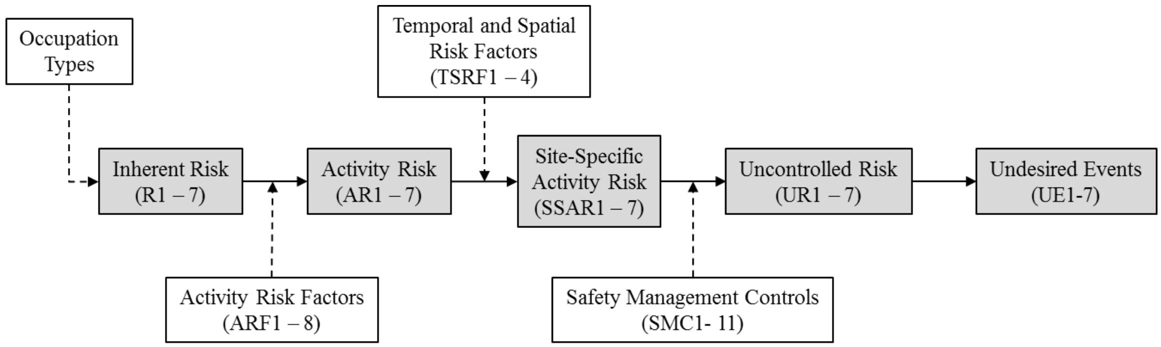



Figure 5: Risk generation and control model

The proposed risk generation and control models can be used in different project stages with available information. As shown in Figure 5, inherent risk (R1-7) represents the baseline assumption that every worker has a chance to be exposed to any types of risk and the extent and types of his/her inherent risk varies by his/her occupation type. Inherent risk should explain the overall safety risk of an occupation and include types and the extent of risk in a quantitative manner to be compared with other occupation types. According to the BLS in 2013, reinforcing iron and rebar workers are 1.6 times more likely exposed to days away injuries than the construction average. In particular, this occupation is 2.5 and 1.6 times more likely exposed to 'Overexertion and bodily reaction' (R7) and 'Falls, slips, trips' (R4), respectively, as compared to the selected risk types of the construction average. Inherent risk in the model explains general risk of a worker and can be used in the early stage of a project to prioritize high risk occupations and prepare safety actions in advance.

Any occupation performs a number of activities. When an activity is assigned to a worker, the extent and type of inherent risk will be specified because the activity determines the resources a worker will use to perform the activity. Therefore, activity risk (AR1-7) in the proposed model is a specified version of inherent risk of a selected occupation with activity resource information. In order to understand the transformation process from inherent risk to activity risk, the relationship between risk types and activity risk factors (ARF1-8) should be defined. For example, Esmaeili et al. (2015b) analyzed the cause and effect relationship between struck-by risk and a number of predictable factors in a quantitative manner. Activity risk can be evaluated when representative activity information, such as equipment or materials, is determined.

Activity risk explained in the model assumes that activity is not influenced by time and location related factors. When specific temporal and spatial contexts of the activities such as work duration, location, or existence of concurrent activities are determined, activity risk will be further specified. Temporal and spatial risk factors (TSRF 1-4) can be obtained from project documents such as a project schedule, and play a role to intensify existing activity risk or create new risk types. For example, the possibility of stuck-by risk when a laborer is working with dump truck will be increased when the activity is performed at night. Also, when this activity is performed on a shoulder of a highway, new risks type such as transportation incidents caused by passenger vehicles can be generated. Therefore, to analyze site-specific activity risk (SSAR1-7), the cause and effect relationship between risk types and temporal/spatial risk factors should be identified.

While activity and site-specific activity risks explain the perspective of risk generation depending on specific contexts of activity, safety management controls (SMC 1-11) explain the side of risk mitigation. For example, roofers working on installing shingles on a roof have high risk of falling to the lower level, which is determined by resources and spatial contexts of the activity. When proper fall protection systems, such as guardrail, safety net, or personal fall arrest systems, are planned and implemented, the extent of such risk can be mitigated. Even though extensive safety management controls are prepared, there is always a chance that risk may be uncontrolled leading to undesired events (UE 1-7).

### 3.5 MODEL APPLICATION

The proposed model demonstrates the process of risk generation and mitigation with activity risk factors, temporal and spatial risk factors, and safety management controls. Having produced the model, the next stage of the research was to apply the model to real-world cases. The purpose of the application was to understand how well the proposed model can explain the general process of risk generation and mitigation on actual accident cases. As mentioned earlier, eight out of 32 fatality cases randomly selected from the NIOSH FACE program were used for model application. To provide further context, two representative cases of the eight are discussed in detail subsequently and the rest of analyzes can be found in Appendix A.

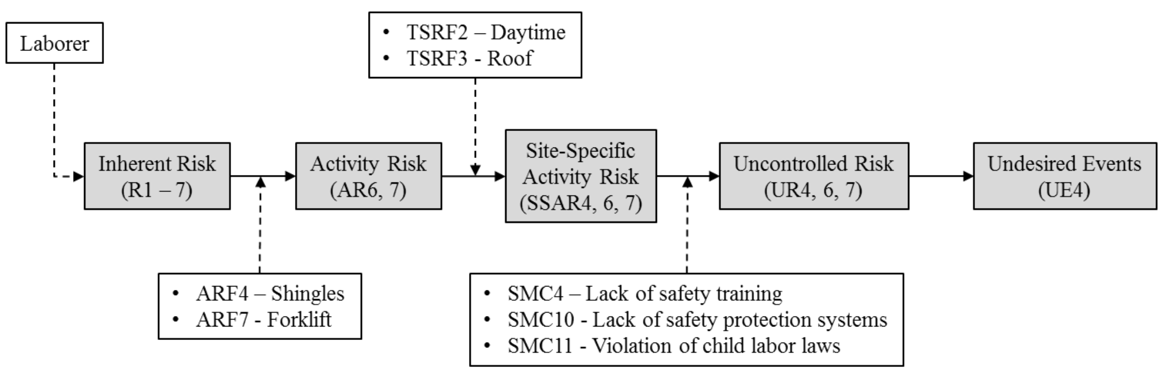



Figure 6: Fatality analysis I

Figure 6 summarized the process of risk generation leading to a fatality. At the time of the accident, a 17-year-old female laborer was working on replacing shingles of a residential roof. According to the Bureau of Labor Statistics, construction laborers showed 1.6 times higher fatality rate than the construction average in 2013 and common risk types related to fatalities were ‘Falls, slips, trips’ (R4), ‘Transportation incidents’ (R2), and ‘Contact with objects and equipment’ (R6) representing 42.8%, 19.5%, and 17.2%, respectively. Based on the accident description, the laborer was involved with two predictable activity risk factors, shingles which belong to ‘Parts and materials’ (ARF4) and forklift which is a part of ‘Vehicles’ (ARF7), and a site-specific risk factor, working on a roof (TSRF3). As a result, this worker was expected to have two types of activity risk which are ‘Contact with objects and equipment’ (AR6) due to forklift (ARF7) and ‘Overexertion and bodily reaction’ (AR7) due to shingles (ARF4). In addition, a spatial context, working on a roof, created an additional risk of ‘Falls, slips, trips’ (SSAR4). The case did not provide detailed information of safety management controls the project implemented, but mainly the jobsite failed to implement safety training (SMC4), safety protection systems (SMC10), and child labor laws (SMC11). As a result, three types of risk remained, leading to a fatality caused by falling from a roof (UE4).

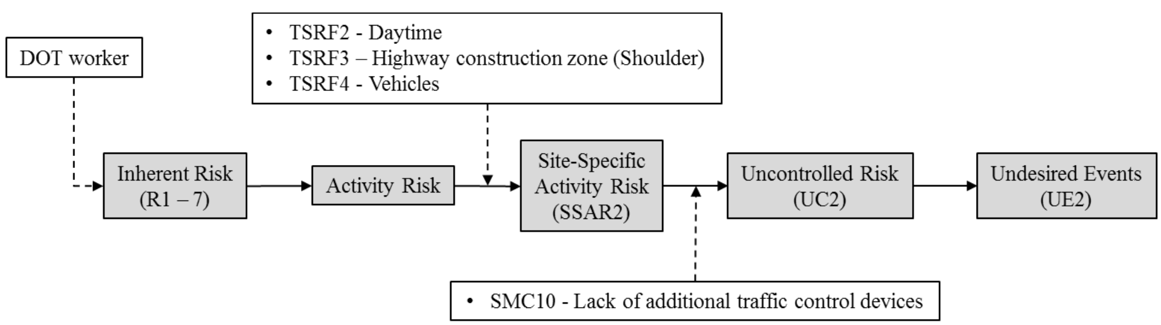



Figure 7: Fatality analysis II

In the second case, a 34-year-old State Department of Transportation worker was preparing for a trench excavation for the following day. The occupation of the victim was not specified in this case. As shown in Figure 7, no critical activity risk factors were observed in the activity. However, the victim was working on a shoulder of a highway

(TSRF3) with public traffic (TSRF4). Due to two temporal and spatial risk factors, the victim was exposed to the risk of 'Transportation incidents' (SSAR4) and struck by a motor vehicle leading to death. The report recommended additional traffic control devices to prevent the accident, but no more information was provided in terms of safety management controls they implemented.

Even though only two representative cases were introduced, all test cases shown in Appendix A successfully explained how risk of a worker was specified by activity, and temporal and spatial risk factors. There was limited information for factors associated with the activities the victim performed because the reports focused on identifying critical causal factors of fatalities. With more detailed information, more comprehensive risk analysis can be performed.

### 3.6 CONCLUSIONS

To enhance the assessment and understanding of why accidents occur, several accident causation models have been developed for the construction industry. These models successfully describe accident causation with comprehensive causal factors and enable the support of accident investigation methods. With growing recognition of proactive safety management, a number of risk analysis methods have been introduced with construction domain knowledge. However, most current risk analysis methods in the construction industry lack a theoretical background and analyzed risk with limited number of measurable factors.

This chapter proposes a risk generation and control model which describes the phenomenon of dynamic safety risk with construction domain knowledge. Based on extensive literature review and analysis of 32 fatality reports from the NIOSH FACE program, the pattern of risk generation and mitigation was examined with predictable risk factors. The model assumes that every worker has inherent risk. When an activity is assigned to a worker, his/her risk is specified based on a number of activity risk and temporal/spatial risk factors. These specified activity risks may be mitigated by management control, and uncontrolled risk results in undesired events.

This chapter focused on providing a theoretical model to aid in practical risk assessment methods by understanding the process of risk generation and mitigation. The following chapter will examine safety risk in quantitative manner.

# Chapter 3 Assessing Safety Risk in Different Construction Trades: A Quantitative Approach

This chapter proposes an innovative quantitative safety risk quantification model to analyze dynamic safety risks for different occupations. In order to consider the dynamic nature of safety risk, models were created for 17 different construction occupations based on injury severities, risk types, and sources of injuries. Two relative injury rates, relative fatality and relative days away injury rates were used to compare relative safety risks among different trade workers. The findings indicate different occupations were exposed to different types of risks and sources of injuries. In addition, the same occupation had different risk types and sources of injury depending on different injury severities. A construction project typically involves numerous workers and resources. The safety risk analysis presented in this chapter can be used by safety managers to understand the dynamic nature of safety risk and aid in preparing safety actions such as inspections or trainings more effectively by focusing on high-risk occupations, risk types, or sources.

## 3.1 Introduction

The construction industry has one of the worst occupational health and safety records of any industries. The Bureau of Labor Statistics in 2013 indicate that the construction industry employs approximately 5.2% of the work force, but accounts for 8.9% of occupational injuries and 20.2% of all occupational fatalities in the United States (BLS 2013). In spite of stringent regulations and much attention towards reducing risks in the physical environment, the construction industry continues to be associated with high levels of accidents, injuries and illnesses.

The high level of risk in the construction industry has been explained by inherent characteristics of the construction industry. One of unique characteristics is the dynamic nature of the construction work environment. Unlike what happens in other industries having static and indoor work environment, construction sites are very dynamic in terms of ground condition, temporal structure, weather conditions, and equipment (Fredericks et al. 2005). The coexistence of work teams with different tasks working in a common area increases the complexity of safety risk profiles. Also, the work teams are in constant rotation throughout the project and their members may also change along the way (Carter and Smith 2006; Hinze 1997; Hinze and Wilson 2000; Yi and Langford 2006).

The most effective way for improving safety performance is to prevent accidents before they occur. In this manner, proactive risk management is important. Typical risk management includes a three-step process: risk identification, risk assessment, and risk mitigation (Tixier et al. 2002). Hallowell and Gambatese (2009) stated typical methods of risk assessment in construction practice focus more on risk identification, and risk evaluation process is typically performed through subjective safety experts' judgement. Due to the lack of tools, frequent and thorough risk analyses at construction sites are hardly ever performed. (Tang et al. 1997). Moreover, hazard identification levels are often far from ideal (Carter and Smith 2006). Also, Rozenfeld et al. (2009) pointed out that risk levels in construction settings fluctuate with dynamic work environment and, thus, uniform levels of investment in proactive safety measures can be illusive and inefficient.

This chapter proposes an innovative safety risk quantification model to understand the dynamic nature of safety risks. By dynamic, I mean the constant changes that occur in the context of work zones in the construction work environment. The proposed model analyzed different risk types and sources of injury associated to different construction occupations based on historical accidents data.

### 3.2 Background Research

In construction project management, safety risk management is important to identify potential hazards, evaluate the risks associated with the hazards, and mitigate them before they occur. As Hallowell and Gambatese (2009) stated, current construction risk management practices focus on risk identification and there is a lack of tools for objective risk assessment. In this section, studies related to risk assessment were reviewed to develop and frame a new risk assessment methodology. Particularly, three aspects of risk assessment were reviewed and compared: primary functions for safety risk assessment, data collection methodology, and target unit of analysis.

Risk has been defined in a variety of ways. As the most common approach, risk is considered as a product of probability and severity. For example, Kumamoto and Henley (1996) defined risk as a collection of all possible pairs of likelihoods and outcomes. Probability is typically defined in terms of the number of injuries or illnesses per worker-hours; severity is defined by the average outcome of the injury or illness (Esmaeili and Hallowell 2013). With this definition, many studies (Baradan and Usmen 2006; Cuny and Lejeune 1999; Esmaeili et al. 2015b; Rozenfeld et al. 2010) focused on the assessment of probability and severity of potential incidents. In addition, Jannadi and Almishari (2003) defined risk as a measure of the probability, severity, and exposure of all the hazards of an activity. Exposure, defined in units of time, typically describes the total time an individual or crew is exposed to a risk (Esmaeili and Hallowell 2013). After Jannadi and Almishari (2003) introduced the third dimension, exposure, to quantify safety risk, several authors (Esmaeili and Hallowell 2013; Jannadi and Almishari 2003; Rozenfeld et al. 2009) quantified safety risk as a product of probability, severity, and exposure.

Even though risk assessment typically involves quantifying safety risks on numerical ways using a combination of three dimensions, safety risk assessment approaches differ primarily based on how they assess the probability, severity, or exposure. Two main approaches are using expert opinions and historical data (Esmaeili et al. 2015a; Esmaeili et al. 2015b; Mitropoulos and Namboodiri 2010). Very few construction firms have the quantity and quality of data needed to perform meaningful safety risk analysis. As a result, several researchers used subjective safety experts' judgement to quantify safety risk. For example, Everett (1999) identified seven common risk factors related to overexertion injuries and quantified each risk using ordinal scoring system (1-3) obtained from expert judgement. Jannadi and Almishari (2003) proposed a risk assessor model (RAM) to quantify the safety risk associated with a particular activity. In their model, activity risk score was calculated using a function of severity, exposure, and probability, which was determined by end-users. Lee and Halpin (2003) developed a fuzzy logic model with safety expert input to predict safety risk of activities related to utility-trenching process based on three critical risk factors: preplanning, training, and supervision. Rozenfeld et al. (2010) proposed 'Construction Job Safety Analysis' (CJSA) for proactive safety risk assessment. Based on extensive survey with safety experts, loss of control events were identified at work stage level and associated risk of each loss of control event was quantified with potential probability and severity determined by users. Although survey-based risk quantification approach enables the use of experiential knowledge of safety professionals, which might be the most valuable asset of the construction industry, this approach cannot escape from biases of subjective judgement. To minimize biases inherent in a survey approach, Hallowell and Gambatese

(2009) quantified severity and the average of frequency for 13 activities using Dephi method. The degree of exposure collected from field observations was then combined with severity and frequency values to quantify a final activity risk. In addition, several researchers applied the analytic hierarchy process (AHP) to prioritize safety risk factors they identified (Aminbakhsh et al. 2013; Badri et al. 2012; Sun et al. 2008).

Other researchers have used statistical injury data to develop a priori estimates of safety risks. In this approach, researchers use historical accident data from national databases such as the Bureau of Labor Statistics (BLS) or accident reports from individual companies. For example, Baradan and Usmen (2006) analyzed relative risks of 16 building trades based on fatal and nonfatal injury data from BLS. Yi and Langford (2006) attempted to estimate activity risk associated with fall hazards considering physical environmental and work process risk factors collected from fatality reports provided by the Korean Occupational Safety and Health Agency. Fung et al. (2010) estimated relative risks of 14 representative construction trades in Hong Kong with 18 types of accidents by considering frequency and severity based on historical accident data. Jacinto and Silva (2010) proposed a semi-quantitative risk assessment methodology in the shipbuilding industry. A bow-tie technique was explored to explain causation and consequence of specific struck-by accident by considering likelihood and potential severity obtained from national historical accident data. Wang et al. (2006) proposed a simulation-based risk assessment model, SimSAFE, to assess the hazard for each activity. The model simulated a list of activity risk by considering estimated likelihood associated with causes of accidents based on historical accident data. Esmaeili et al. (2015b) developed an attribute-based risk assessment model. Using numerous accident reports obtained from the Occupational Safety and Health Administration (OSHA) Integrated Management Information System (IMIS), measureable safety attributes were identified and probability of struck-by accident in a specific activity scenario was quantified from the combination of related safety attributes. Maiti and Bhattacherjee (1999) examined effects of five safety factors on degree of injuries to miners in India. Based on four years data for both the injured and uninjured miners, relative effect of each factor on degree of injuries was analyzed using logistic aggression approach.

In addition to data collection approaches, target units of risk assessment also vary, such as project-, trade-, activity-, or attribute-level. Sun et al. (2008) assessed the risky level of Beijing Olympic venues construction projects, and Baradan and Usmen (2006) compared riskiness of 16 construction trades. These units of analyses enable the comparison of high level inherent risk, but fail to provide detailed potential hazards generated from the dynamic nature of construction process. Several researchers attempted to quantify safety risk at an activity level (Esmaeili and Hallowell 2013; Everett 1999; Hallowell and Gambatese 2009; Jannadi and Almishari 2003; Lee and Halpin 2003; Yi and Langford 2006). However, as Esmaeili et al. (2015a) pointed out, quantifying safety risks of all construction activities are impractical and time-consuming, especially when a survey-based data collection method is adapted. Recently, Esmaeili et al. (2015b) introduced an attribute-based risk analysis approach. In their model, safety risk of an activity is quantified based on a combination of safety risks of predictable attributes quantified from historical data. This attribute-based risk assessment model enables one to address the dynamic nature of a construction activity with safety attributes being selected by users depending on the work environment of an activity. However, the current attribute-based risk assessment model has two limitations. First, the model is limited to analysis of struck-by hazards types, which need to be extended to other hazard types, such as fall hazard. Second, this model assumed that a risk score of an attribute would be the same regardless of different trades. However, different occupations might have different frequency and severity of safety attributes. For example, a roofer and a construction equipment operator might have different risk when they use the same tool, such as a ladder, because the location or purpose of use of the ladder is inherently different.

The extensive literature shows that using empirical data is important to obtain reliable risk assessment. Also, to address the dynamic nature of construction work process, an attribute-based risk assessment considering the unique nature of different trades is needed.

## 3.3 Research Method

### 3.3.1 Conceptual Safety Risk Quantification Model

The underlying assumption of the proposed risk quantification model is that every worker contains an inherent risk. However, the extent of inherent risk varies by occupations due to the unique activity assigned to them. Depending on the nature of an activity assigned to different occupations, inherent injury types vary. For example, roofers have higher fatality rates when compared to other occupations due to the nature of working at height. Reinforcing iron and rebar workers have more possibilities of getting injured, mostly days away injuries because reinforcing iron and rebar workers are likely to work on unstable/uneven surfaces, especially working on rebar. Risk types such as falls or struck-by objects vary by injury types as well as different occupations. According to the BLS 2013, 'falls, slips, and trips' was the most prevalent events of fatalities while 'contact with objects and equipment' was the major events of days away injuries within construction trade workers. Therefore, safety risk of different occupations should be analyzed by different injury severities and risk types to understand dynamic nature of safety risk. In addition, each risk type for every occupation has different sources of injuries. For example, ladders are used extensively by painters and, thus, ladders are one of main sources of fall hazards within painters. Structural iron and steel workers frequently involve heavy material transportation, and, thus, are easily exposed to hazards related to struck-by objects. By quantifying safety risks of sources by risk types, the proposed model enables the understanding of how the extent of certain hazard types can vary depending on sources utilized within an activity. Figure 8 conceptually illustrates the scenarios explained above.

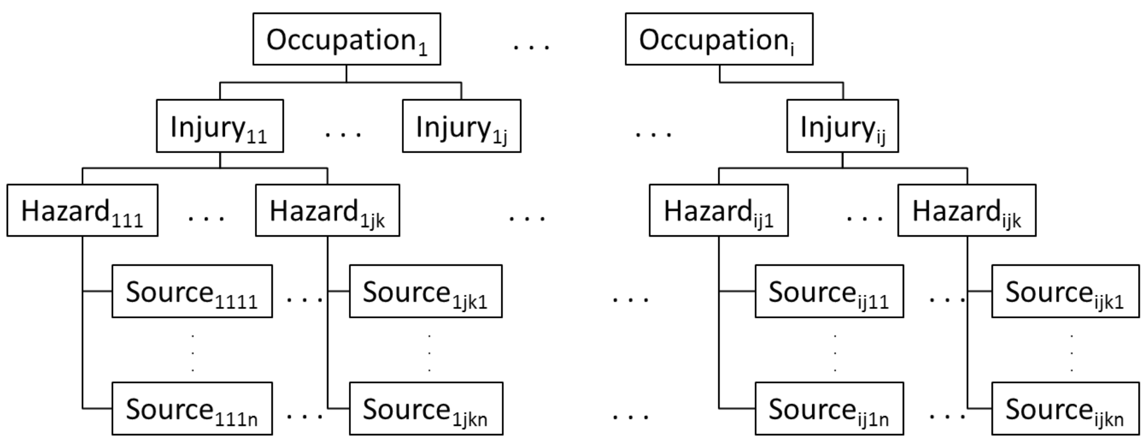



Figure 8: Conceptual risk assessment model

### 3.3.2 Data Collection

The BLS Injuries, Illnesses, and Fatalities (IIF) program provides several historical statistics related to injury severities, risk types, and sources of injury by different occupations. Within the BLS IIF program, fatalities and days away injuries have been collected from the Census of Fatal Occupational Injuries (CFOI) and Survey of Occupational Injury and Illness (SOII), respectively. The BLS CFOI has collected occupational fatal injury data from both private and public sectors while the BLS SOII has estimated non-fatal workplace injuries and illnesses from the private sector. For consistency, injury data from only the private sector was reviewed for both fatal and days away injury data. Accident types and primary sources of injuries were classified based on Occupational Injury and Illness Classification System (OIICS). In terms of occupation data, 19 construction occupations were selected based on the 2010 Standard Occupational Classification (SOC) system which was adapted for the BLS CFOI and SOII. In addition, to normalize the number of two injury cases by the number of employment, employment size in the private sector of different occupations was collected from the BLS Occupational Employment Statistics (OES). In this study, all data analyzed were from the 2013 private construction sector. Figure 9 summarizes data sources and classification systems used for this study.

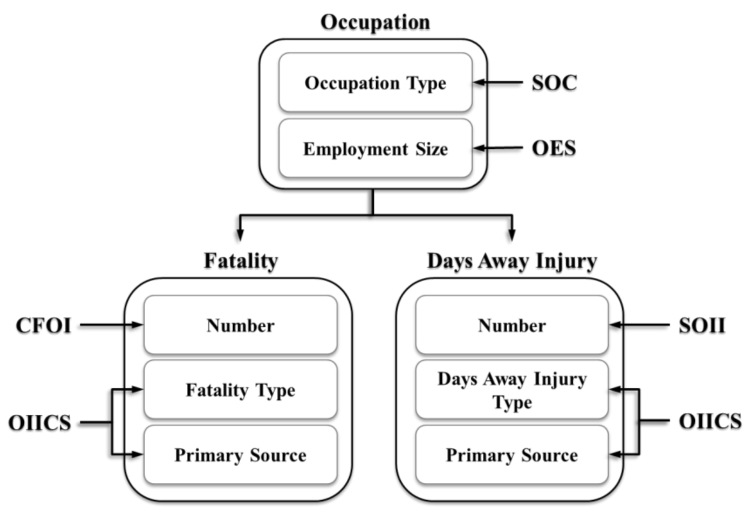



Figure 9: Data sources and classification systems

### 3.3.3 Analysis Steps

***Identification overall relative safety risk by occupations***

In order to analyze safety risk of different construction occupations, first of all, overall safety risks of 19 different construction trades were analyzed in terms of two injury severities, fatality and days away injury. To quantify the overall safety risks associated with 19 construction occupations, historical injury data was reviewed. The objective was to quantify and compare relative safety risk of different construction occupations based on historical accident data. From the BLS CFOI and OES, fatality rate was calculated representing the number of fatalities per 100,000 full time equivalent workers. Days away injury rate was calculated based on the BLS SOII and OES, and this rate represents the number of days away injuries per 10,000 full time equivalent workers. In order to compare with construction average injury rate, two types of relative injury rates, relative fatality rate (RFR) and relative days away injury rate (RDAIR), were created. Relative fatality and days away injury rates of an occupation i, denoted as RFRi and RDAIRi are represented as:

$$\textit{\textbf{Relative fatality rate}}_i\ \textit{\textbf{(RFR) = Fatality rate}}_i\ \textit{\textbf{/ Fatality rate}}_{avg.}$$

$$\textit{\textbf{Relative days away injury rate}}_i\ \textit{\textbf{(RDAIR) = Days away injury rate}}_i\ \textit{\textbf{/ Days away injury rate}}_{i.}$$

In which fatality $\text{rate}_i$ and fatality $\text{rate}_{avg}$ denotes a fatality rate of occupation i and average of construction trade workers, respectively, and days away injury $\text{rate}_i$ and days away injury $\text{rate}_{avg}$ indicates a days away injury rate of occupation i and average of construction trade workers, respectively.

Two relative safety injury rates used in this chapter enable the understanding of how different construction occupations have different safety risks by two different injury severity types compared to overall construction trade workers.

***Identify specific risk types by occupations***

Even though two relative injury rates provide overall risk level of different construction occupations, these indicators cannot explain which accident types specific occupations are more frequently exposed to. Therefore, quantifying specific risk types by different occupations is valuable.

The first step of quantifying specific risk types is the classification of common construction safety risks. In this analysis, the Occupational Injury and Illness Classification System (OIICS) was selected to define and classify safety risk types. The OIICS defines 'Events or Exposure' of injuries at four hierarchical levels with four digit code systems, henceforth denoted as 'E'. The OIICS includes seven 1st level, 48 2nd level, 178 3rd level, and 304 4th level injury types. For example, 'Falls, Slips, Trips' (E4) has seven 2nd level injury types including 'Fall to lower level' (E43), and E43 can break down into four additional 3rd level injury types including 'Fall through surface or existing opening' (E432) which further breaks down into eight 4th level injury types such as 'Fall through surface or existing opening 11 to 15 feet' (E4323). After defining specific risk types, number of fatalities and days away injuries by detailed risk types were collected from the BLS CFOI and SOII, respectively. Due to the data availability, both fatality and days away injury data was analyzed by 2nd level injury types by different occupations.

***Identify specific sources by specific risks***

Identification of specific risk types enables the understanding of how different construction trades are exposed to different risk types. However, there is still no information about sources of risks, which can help explain why certain risk will possibly happen. Therefore, understanding common sources of injuries by different occupations is important. Also, possible accident scenarios can be obtained by linking specific sources of injuries and specific risk types since they have a cause and effect relationship.

First of all, common sources of injuries were identified from the OIICS. Similarly to risk types, the OIICS classified 'Primary Sources of Injury' at four hierarchical level with corresponding codes, denoted as 'S' in the rest of paper. The OIICS defines nine 1st level, 78 2nd level, 439 3rd level, and 1139 4th level sources of injury. For example, 'Tools, Instruments, and Equipment' (S7) has 10 2nd level sources of injury including 'Ladders' (S74), and S74 can break down into four additional 3rd level sources including 'Ladders – movable' (S742) which further break down into six 4th level sources such as 'Extension ladders' (S7421). With the definition of sources, numbers of fatalities and days away injuries by detailed sources of injury were analyzed from the BLS CFOI and SOII, respectively. In addition to the identification of common sources of injuries by different construction trades, common injury scenarios were identified by linking sources of injury and risk types. Due to the data availability, sources of injury were also analyzed by 2nd level. Therefore, the analysis in this study is limited to 2nd levels of risk types and sources of injury. For instance, a possible injury scenario is 'Fall to lower level' (E43) due to 'Ladders' (S74).

## 3.4 Results

### 3.4.1 Overall Risk by Occupations

During the data analysis, two occupations out of 19 were excluded due to the relatively small employment sizes and a significant amount of missing data. Therefore, a total of 17 construction occupations and overall construction trade workers were selected for the analysis as shown in Table 5.

Table 5: Construction Occupations and Corresponding Codes

| Code | Title | Code | Title |
|---|---|---|---|
| 47-2000 | Construction Trades Workers | 47-2120 | Glaziers |
| 47-2020 | Brickmasons, Blockmasons, and Stonemasons | 47-2130 | Insulation Workers |
| 47-2030 | Carpenters | 47-2140 | Painters and Paperhangers |
| 47-2040 | Carpet, Floor, and Tile Installers and Finishers | 47-2150 | Pipelayers, Plumbers, Pipefitters, and Steamfitters |
| 47-2050 | Cement Masons, Concrete Finishers, and Terrazzo Workers | 47-2160 | Plasterers and Stucco Masons |
| 47-2060 | Construction Laborers | 47-2170 | Reinforcing Iron and Rebar Workers |
| 47-2070 | Construction Equipment Operators | 47-2180 | Roofers |
| 47-2080 | Drywall Installers, Ceiling Tile Installers, and Tapers | 47-2210 | Sheet Metal Workers |
| 47-2110 | Electricians | 47-2220 | Structural Iron and Steel Workers |

Source: Standard Occupational Classification (SOC)

For each occupation, two relative injury rates in 2013 were estimated as illustrated in Figure 10. In this figure, the x-axis indicates relative days away injury rate (RDAIR) and the y-axis represents relative fatality rate (RFR). The dotted vertical and horizontal lines at 100 indicate the average days away injury and fatality rates for overall construction trade workers.

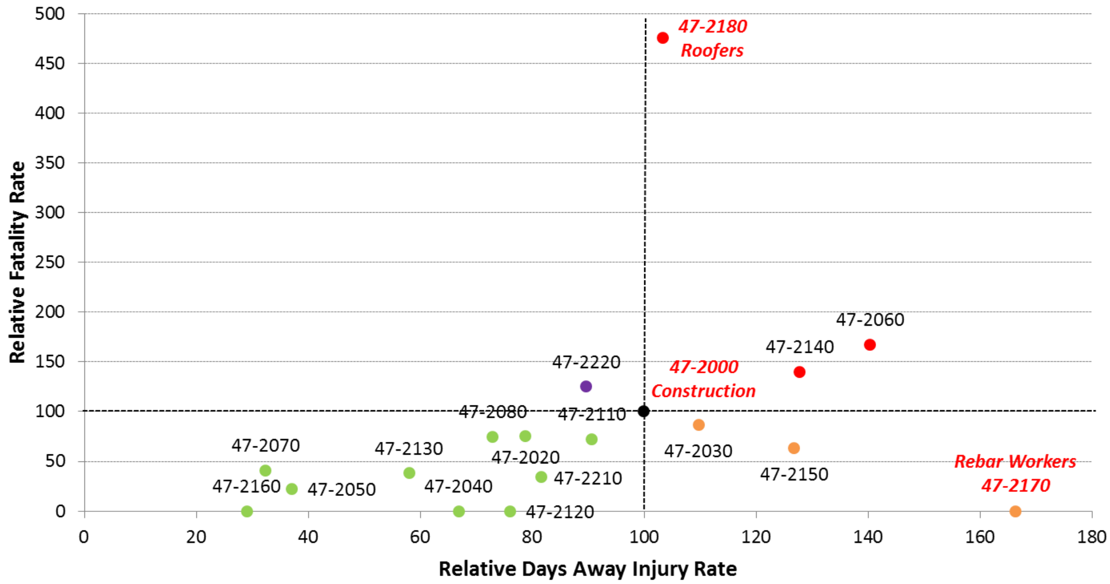



Figure 10: RFR and RDAIR for 17 construction occupations (Red: high RFR and high RDAIR, Purple: high RFR and low RDAIR, Orange: low RFR and high RDAIR, Green: low RFR and low RDAIR)

As shown in Figure 10, different construction trades had different injury frequencies in terms of two injury severity types, fatality and days away injury. For example, roofers (47-2180) had extremely high fatality rate, more than 4.5 times higher than the construction average, while reinforcing iron and rebar workers (47-2170) experienced the highest days away injury rate, approximately 1.65 times higher than the construction average, with no fatalities in 2013. In addition, roofers (47-2180), construction laborers (47-2060), and painters and paperhangers (47-2140) were examined as dangerous occupations in terms of both injury indicators compared to the overall construction trade workers. Analysis of RFR and RDAIR shows that different construction occupations have different inherent risks.

### 3.4.2 Specific Risk by Occupations

Two relative injury indicators in Figure 10 represent the overall fatality and days away injury rates of different construction occupations compared to the construction industry average in 2013. However, there is a need to identify specific risk types related to each occupation because different safety actions should be required depending on expected risk types. For example, construction laborer (47-2060) and painters and paperhangers (47-2140) in Figure 10 showed similar RFR and RDAIR, but they require different safety barriers to mitigate their risks due to the different specific risk types of the two occupations.

Out of seven 1st level and 48 2nd level risk types identified from the OIICS, all of 1st level and 33 2nd level risk types were related to either fatality or days away injury within construction trade workers in 2013. In the analysis, six 1st level (except for 'FIRES AND EXPLOSIONS' (E3)) and 26 2nd level risk types were finally selected by discarding risk types with lower than 1.0 of RFR and RDAIR. Table 6 summarizes final specific risk types related to one of 17 construction occupations.

Table 6: Events or Exposures (Risk Types) and Corresponding Codes

| 1st level | | 2nd level | |
|---|---|---|---|
| **Code** | **Title** | **Code** | **Title** |
| E1 | VIOLENCE AND OTHER INJURIES BY PERSONS OR ANIMALS | E11 | Intentional injury by person |
| | | E12 | Injury by person—unintentional or intent unknown |
| E2 | TRANSPORTATION INCIDENTS | E22 | Rail vehicle incidents |
| | | E24 | Pedestrian vehicular incidents |
| | | E25 | Water vehicle incidents |
| | | E26 | Roadway incidents involving motorized land vehicle |
| | | E27 | Nonroadway incidents involving motorized land vehicles |
| E4 | FALLS, SLIPS, TRIPS | E40 | Fall, slip, trip, unspecified |
| | | E41 | Slip or trip without fall |
| | | E42 | Falls on same level |
| | | E43 | Falls to lower level |
| | | E44 | Jumps to lower level |
| E5 | EXPOSURE TO HARMFUL SUBSTANCES OR ENVIRONMENTS | E51 | Exposure to electricity |
| | | E53 | Exposure to temperature extremes |
| | | E55 | Exposure to other harmful substances |
| | | E56 | Exposure to oxygen deficiency, n.e.c. |
| E6 | CONTACT WITH OBJECTS AND EQUIPMENT | E60 | Contact with objects and equipment, unspecified |
| | | E62 | Struck by object or equipment |
| | | E63 | Struck against object or equipment |
| | | E64 | Caught in or compressed by equipment or objects |
| | | E65 | Struck, caught, or crushed in collapsing structure, equipment, or material |
| | | E66 | Rubbed or abraded by friction or pressure |
| E7 | OVEREXERTION AND BODILY REACTION | E70 | Overexertion and bodily reaction, unspecified |
| | | E71 | Overexertion involving outside sources |
| | | E72 | Repetitive motions involving microtasks |
| | | E73 | Other exertions or bodily reactions |

Source: Occupational Injury and Illness Classification System (OIICS)

Based on the list of risk types identified in Table 6, specific risks related to 17 construction occupations were estimated. Figure 11 shows proportions of risk types related to construction trade workers (47-2000), reinforcing iron and rebar workers (47-2170), and roofers (47-2180). Numbers in parenthesis indicate total numbers of fatalities and days away injuries within the selected occupations. Proportions of risk types for the other occupations can be found in Appendix B.

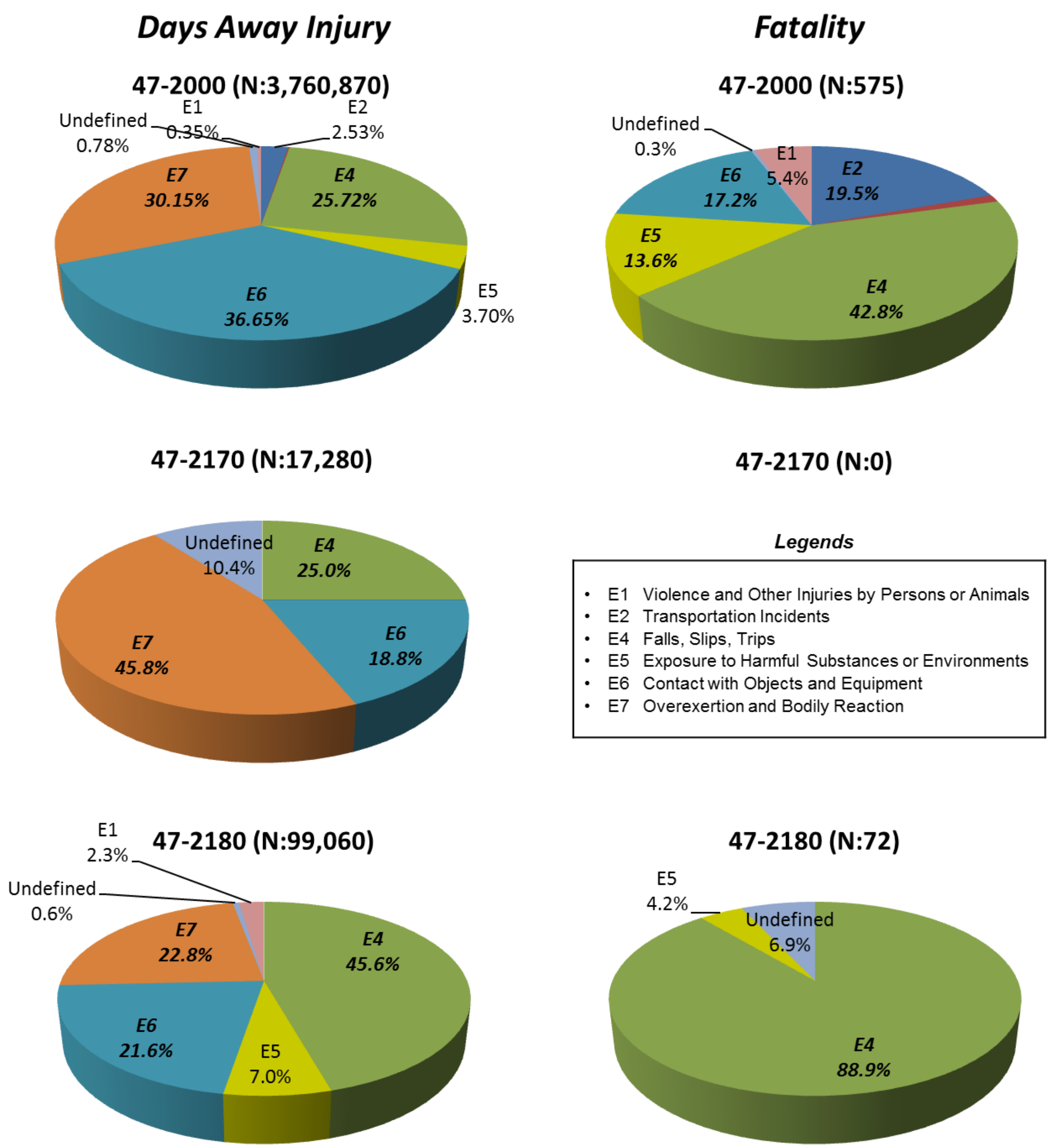



Figure 11: Proportions of 1st level risk types by selected occupations

As shown in two pie charts at the top of Figure 11, construction trade workers (47-2000) had different proportions of risk types in two injury severities. Regarding days away injury of construction trade workers, 'Contact with objects and equipment' (E6) was the most frequent risk type representing 36.65%, and followed by ‘Overexertion and bodily reaction’ (E7) and ‘Falls, slips, trips’ (E4) representing 30.15% and 25.72%, respectively. In terms of fatality, ‘Falls, slips, trips’ (E4) was the dominant risk type with 42.8%, followed by ‘Transportation incidents’ (E2), ‘Contact with object and equipment’ (H6), ‘Exposure to harmful substances or environments’ (E5). Also, when proportions of three different construction trades were compared, they have different risk types by occupation types.

The 2nd level risk types were also analyzed. Figure 12 represents detailed risk types of ‘reinforcing iron and rebar workers’ (47-2170) and ‘roofers’ (47-2180) comparing to ‘construction trade workers’ (47-2000). In this figure, the x-axis indicates 2nd level risk types and the y-axis shows RDAIR. In addition, values in parenthesis next to each occupation indicate their overall RDAIR, and a height of bar indicates a RDAIR of a selected risk type of a selected occupation. RFA and RDAIR analyses of the 2nd level risk types for all occupations can be found in Appendix C.

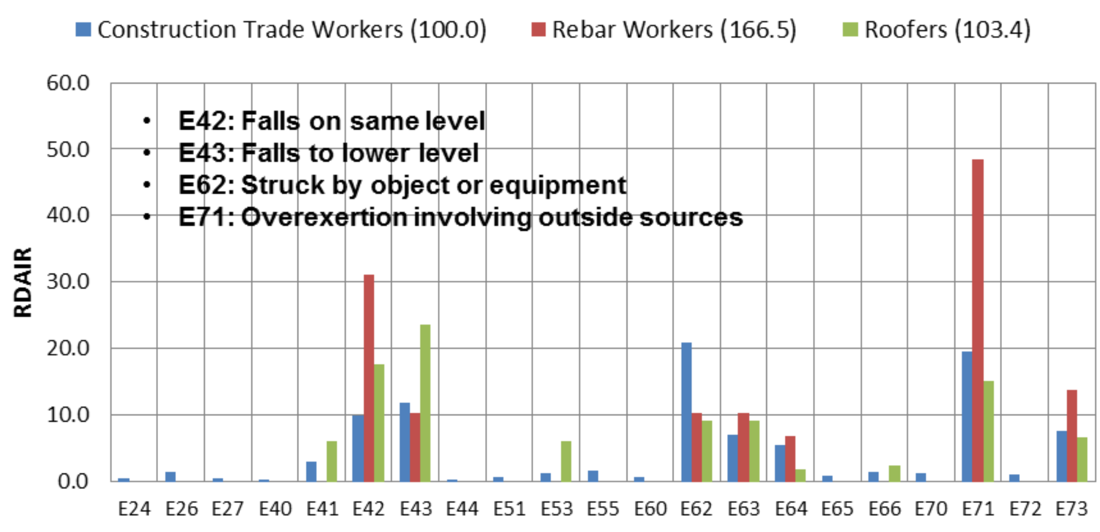



Figure 12: RDAIR of 2nd level risk types by selected occupations

As shown in Figure 12, ‘Struck by object or equipment’ (E62) was the most frequent days away injury type in the construction industry while ‘Overexertion involving outside sources’ (E71) and ‘Falls to lower level’ (E43) were the most frequent injury types for ‘reinforcing iron and rebar workers’ (47-2170) and ‘roofers’ (47-2180), respectively. Also, from the comparison of the same risk types by different occupations, relative magnitude of injury frequency of an occupation was also examined.

From the specific risk analysis, it was found that different occupations were exposed to different types of risks. In addition, even the same occupation, workers experienced different risks by fatality and days away injury. Therefore, it is important to understand the dynamic nature of inherent safety risk types by occupations and injury severity to prepare safety actions effectively.

### 3.4.3 Specific Sources of Injury by Occupations

The objective of identifying and quantifying sources of injuries is to explain the causes of potential injuries. Out of nine 1st level and 78 2nd level sources identified from the OIICS, all of 1st level and 50 2nd level sources were related to either fatality or days away injury within construction trade workers in 2013. In this analysis, nine 1st level and 32 2nd level sources were finally selected by discarding sources representing lower than 1.0% of RFR and RDAIR. Table 7 summarizes final specific sources of injuries related to one of 17 construction occupations.

Table 7: Primary Sources of Injuries and Corresponding Codes

| 1st level | | 2nd level | |
|---|---|---|---|
| **Code** | **Title** | **Code** | **Title** |
| S1 | CHEMICALS AND CHEMICAL PRODUCTS | | |
| S2 | CONTAINERS, FURNITURE AND FIXTURES | S21 | Containers |
| | | S22 | Furniture and fixtures |
| S3 | MACHINERY | S32 | Construction, logging, and mining machinery |
| | | S33 | Heating, cooling, and cleaning machinery and appliances |
| | | S34 | Material and personnel handling machinery |
| | | S35 | Metal, woodworking, and special material machinery |
| | | S37 | Special process machinery |
| | | S39 | Miscellaneous machinery |
| S4 | PARTS AND MATERIALS | S41 | Building materials—solid elements |
| | | S42 | Fasteners, connectors, ropes, ties |
| | | S44 | Machine, tool, and electric parts |
| | | S46 | Tars, sealants, caulking, insulating material |
| S5 | PERSONS, PLANTS, ANIMALS, AND MINERALS | S55 | Nonmetallic minerals, except fuel |
| | | S56 | Person—injured or ill worker |
| | | S57 | Person—other than injured or ill worker |
| | | S58 | Plants, trees, vegetation—not processed |
| S6 | STRUCTURES AND SURFACES | S61 | Confined spaces |
| | | S62 | Buildings—office, plant, residential |
| | | S63 | Structures other than buildings |
| | | S65 | Other structural elements |
| | | S66 | Floors, walkways, ground surfaces |
| S7 | TOOLS, INSTRUMENTS, AND EQUIPMENT | S70 | Tools, instruments, and equipment, unspecified |
| | | S71 | Handtools—nonpowered |
| | | S72 | Handtools—powered |
| | | S73 | Handtools—power not determined |
| | | S74 | Ladders |
| | | S79 | Other tools, instruments, and equipment |
| S8 | VEHICLES | S84 | Highway vehicles, motorized |
| | | S86 | Off-road and industrial vehicles—powered |
| | | S87 | Plant and industrial vehicles—nonpowered |
| S9 | OTHER SOURCES | S92 | Environmental and elemental conditions |
| | | S94 | Scrap, waste, debris |

Source: Occupational Injury and Illness Classification System (OIICS)

Based on the list of sources identified in Table 7, RFR and RDAIR of specific sources of injuries related to 17 construction occupations were estimated. Figure 13 shows proportions of primary sources of injuries related to construction trade workers (47-2000), reinforcing iron and rebar workers (47-2170), and roofers (47-2180). Numbers in parenthesis indicate total numbers of fatalities and days away injuries within the selected occupations. Analyzes for all occupations types can be found in Appendix D.

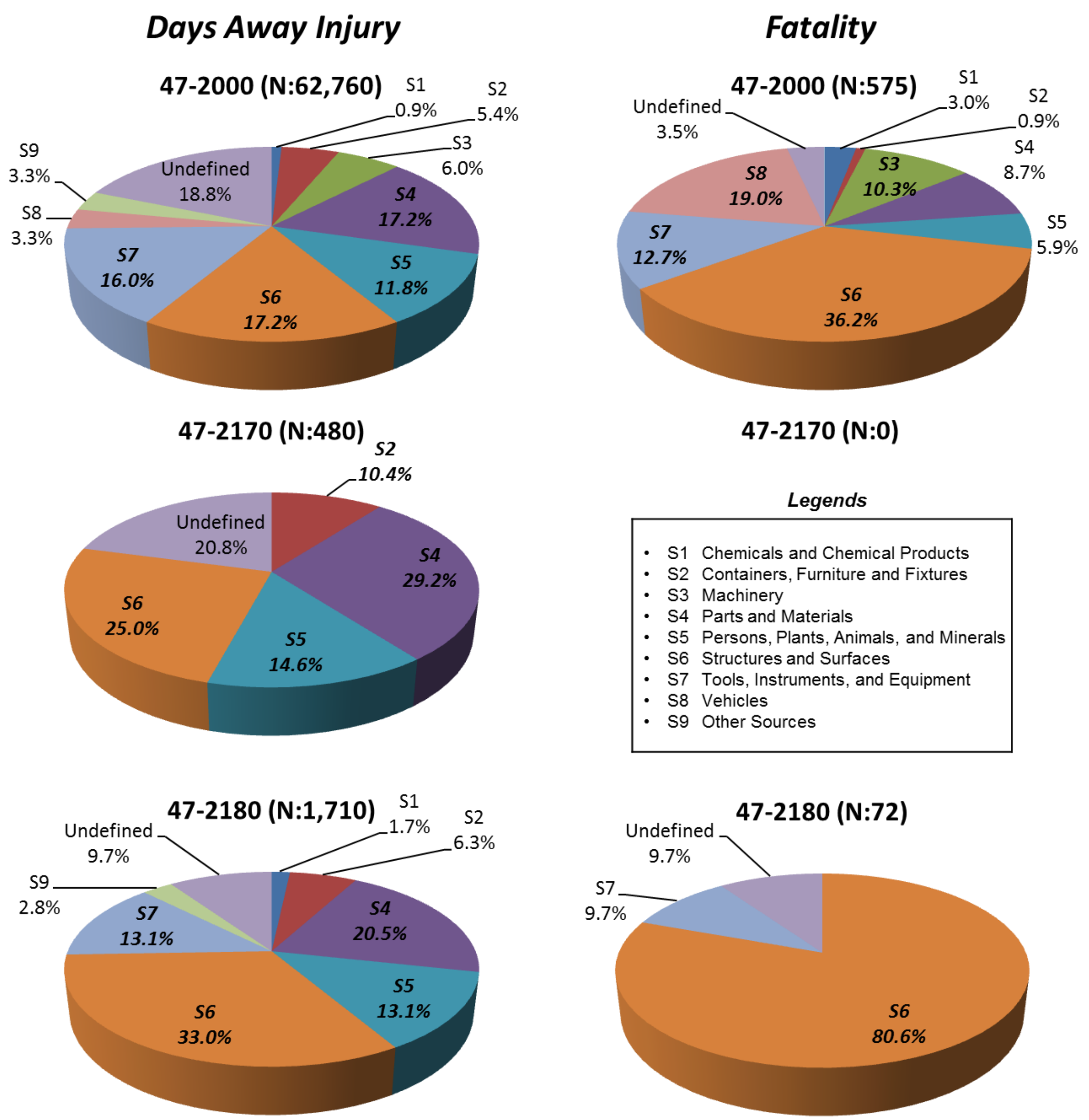



Figure 13: Proportions of 1st level primary sources by selected occupations

Similarly to proportions of specific risk types represented in Figure 11, primary sources of injuries vary by occupation types and injury severity types. As shown in Figure 13, 'Parts and Materials' (S4), 'Structures and surfaces' (S6), and 'Tools, instruments, and Equipment' (S7) are the top three primary sources of fatalities indicating 17.2%, 17.2%, and 16.0%, respectively, within the construction trade workers (47-2000). 'Structures and surfaces' (S6), 'Vehicles' (S8), and 'Tools, instruments, and Equipment' (S7) are main sources representing 36.2%, 19.0%, and 12.7% of days away injuries, respectively. For roofers (47-2180), 'Structures and surfaces' (S6) is the most frequent sources of two injury severity types, but their proportions and diversity of sources are quite different.

The 2nd level sources of injury were also analyzed for fatality and days away injury by 17 different construction occupations. Figure 14 represents detailed primary sources of day away injuries for 'reinforcing iron and rebar workers' (47-2170) and 'roofers' (47-2180) comparing to 'construction trade workers' (47-2000). In this figure, the x-axis indicates 2nd level sources and the y-axis shows RDAIR. In addition, values in parenthesis next to each occupation indicate their overall RDAIR, and a height of bar indicates a RDAIR of a selected primary source of a selected occupation. RFA and RDAIR analyzes of the $2^{nd}$ level primary sources for all occupations can be found in Appendix E.

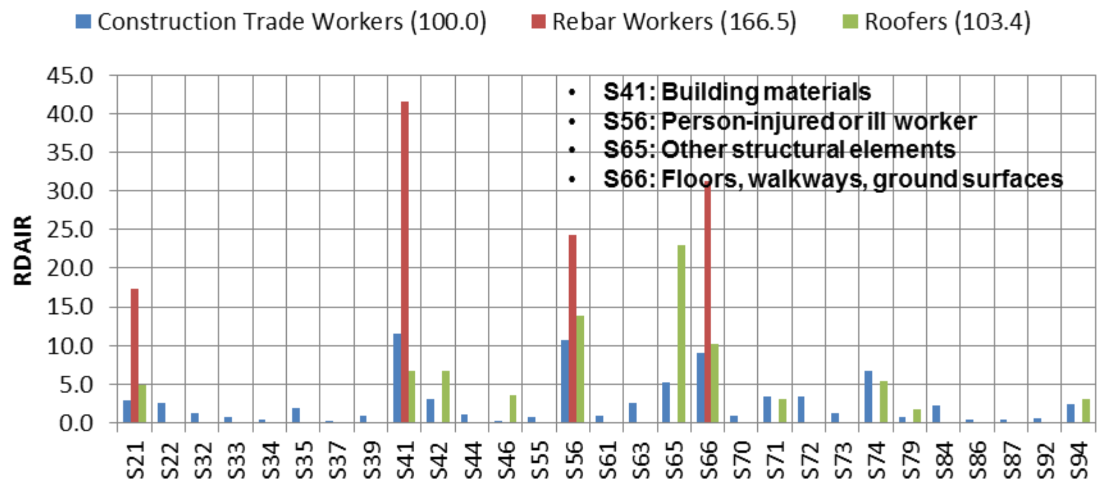



Figure 14: RDAIR of 2nd level primary sources by selected occupations

As shown in Figure 14, 'Building materials-solid elements' (S41) was the most frequent primary source of days away injury for construction trade workers (47-2000) and reinforcing iron and rebar workers (47-2170) while 'Other structural elements' (S65) which includes roofs was the most frequent sources of days away injury for roofers (47-2180).

Primary sources of injury analysis showed that different sources contributed to injuries of different occupations. In addition, even within the same occupation, workers were injured by different sources depending on injury severity types. Therefore, it is important to understand the dynamic sources of injury by occupations and injury severities to prepare safety actions effectively.

**3.4.4 Specific Risk Scenarios by Occupations**

In Figure 12, 'Struck by object or equipment' (E62) was identified as the most frequent risk type of days away injury, and in Figure 14, 'Building materials-solid elements' (S41) was identified as the most frequent primary source of days away injury. However, it is hard to say that 'Struck by object or equipment' (E62) was caused by only

‘Building materials-solid elements’ (S41) because risk types and sources have a many to many relationship. There might be other sources that led to ‘Struck by object or equipment’ (E62) such as ‘Handtools-nonpowered’ (E71) or ‘Scrap, waste, debris’ (S94). Also, it is possible that ‘Building materials-solid elements’ (S41) resulted in multiple risk types such as ‘Overexertion and bodily reaction’ (E7) as well as ‘Struck by object or equipment’ (E62). The objective of analyzing risk scenarios is to identify many to many relationships between primary sources and specific risk types, and understand various risk scenarios by different occupations.

Data about the relationship between primary sources of days away injury by 17 construction occupations was obtained from the BLS SOII, but equivalent data related to fatality was only available for only overall US industries from the BLS CFOI. However, the overall US industrial data cannot capture the unique nature of the construction industry. For example, ‘Construction, logging, and mining machinery’ (S32) is one of the main primary sources of fatalities in the construction industry, especially for ‘Construction Equipment Operators’ (47-2070), but this source is regarded as a minor source of overall industrial fatalities. Since the disproportion of primary sources of fatalities between overall industries and the construction industry, possible fatality scenarios and their magnitudes were not considered in this analysis. Figure 15 illustrates days away injury risk scenarios of construction trade workers (47-2000).

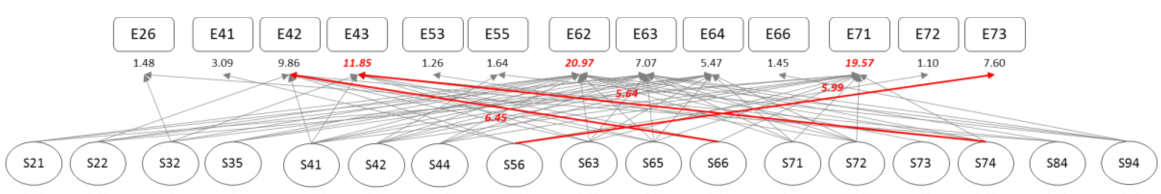



Figure 15: Days away injury risk scenarios of construction trade workers (47-2000)

As can be seen Figure 15, the relationship between primary sources of days away injuries and specific risk types is complicated. For days away injuries, 'Falls on same level due to floors, walkways, ground surfaces' (S66-E42), 'Other exertions or bodily reactions due to person-injured or ill workers (S56-E73), and 'Falls to lower level due to ladders' (S74-E43) are the top three most frequent injury scenarios representing 7.68%, 7.13%, and 6.72% of days away injuries, respectively. E62 which was identified the most frequent risk type of days away injuries was caused by 14 different sources out of 17 sources, and S41 which was examined as one of the most critical sources of days away injuries which resulted in six different risk types.

### 3.4.5 Final Risk Quantification Model

The purpose of the risk quantification model is to quantitatively explain why and how much a construction worker will be in danger based on historical accident data. In the proposed model, overall and specific risk, sources of risk, and risk scenario estimated from previous sections were integrated into a single data structure by each construction occupation based on the data hierarchy presented in Figure 8. Figure 16 illustrates the final risk quantification model of construction trade workers (47-2000). Final risk quantification models for all occupations can be found in Appendix F.

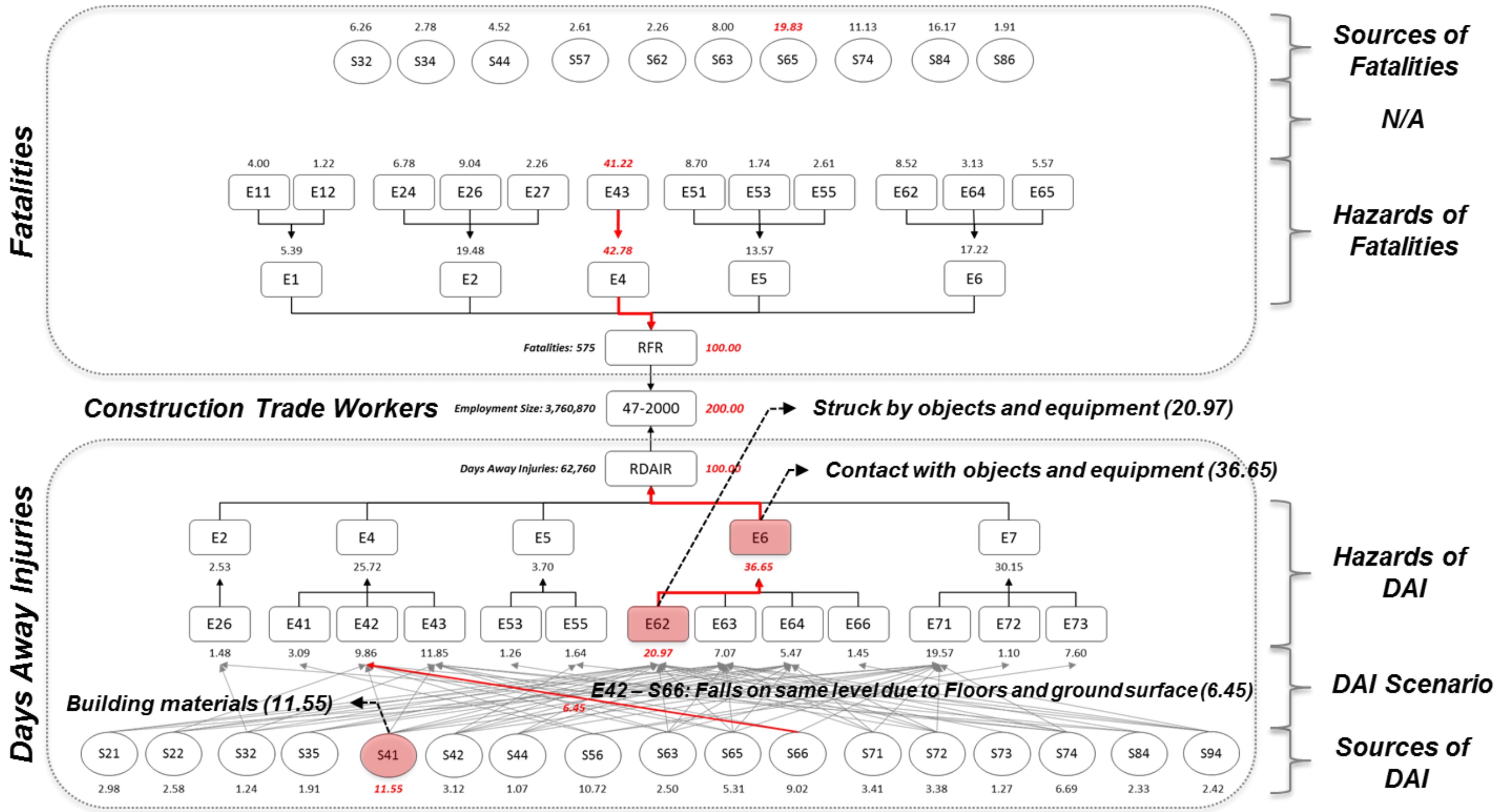



Figure 16: Risk quantification model of construction trade workers (47-2000)

In Figure 16, the code in the middle indicates occupation type, the upper part of the code is about fatality related data, and the lower part explains days away injury related data for the selected occupation. The overall safety risk of the occupation was calculated by summating RFR and RDAIR of the occupation and each relative injury rate was decomposed into hazard types and sources of injuries. Ex (1st level risk type) and Exx (2nd level risk type) explain relative frequency of risk types an occupation was exposed to. Sxx represents 2nd level primary sources of fatalities (top) and days away injuries (bottom), and links between Sxx and Exx indicate cause and effect relationship between sources and hazards representing injury scenarios. In the model, the sum of the lower levels does not equal to a RFR or RDAIR of the higher level because there were missing data and only risk types and sources of injuries with more than 1% of RFR and RDAIR were represented. Table 8 summarizes data representatives by hierarchical levels. Data representatives for all occupations also can be found in Appendix F.

Table 8: Summary of Data Representative by Hierarchical Level

| | Total | 1st level risk (Ex) | 2nd level risk (Exx) | 2nd level source (Sxx) | 2nd level risk scenario |
|---|---|---|---|---|---|
| RFR | 100.00 | 99.65 | 94.78 | 75.83 | N/A |
| RDAIR | 100.00 | 98.74 | 92.40 | 71.51 | 66.87 |

As can be seen Figure 16, the overall safety risk of construction trade workers (48-2000) is 200.00. The most critical 1$^{st}$ and 2$^{nd}$ hazard type of days away injuries are ‘Contact with objects and equipment’ (E6) and ‘Struck by objects and equipment’ (E62) representing 34.65 and 20.97 out of 100.00. The most common source of days away injuries is ‘Building materials’ (S41) indicating 11.55. Also, the most common days away injury scenario is ‘Falls on same level due to Floors and ground surface’ (E42-S66) representing 6.45 out of 100.00.

Using the model, we can understand common hazard types, sources of injury, and injury scenarios by different occupations. The findings show that every occupation has a unique pattern of safety data structure in terms of hazards and sources of injuries and, thus, this is a good justification of why safety risk should be analyzed by different occupations.

### 3.5 Applications

Two relative injury indicators estimated by different hierarchical levels in this chapter can be used by managers including project managers, safety managers, site managers, or superintendents to mitigate the expected safety risk in different ways. A construction project typically involves numerous workers and resources. If safety risk levels could be reliably estimated by occupations, risk types, and sources, strategic safety plan could be established such as inspections and training on high-risk occupations. For example, relative injury rate data of selected risk type by different occupations enable the preparation of a safety plan or more effective training by focusing on high-risk occupations. Figure 17 shows relative fatality rate (RFR) of ‘Fall to lower level’ (E43) by different construction occupations.

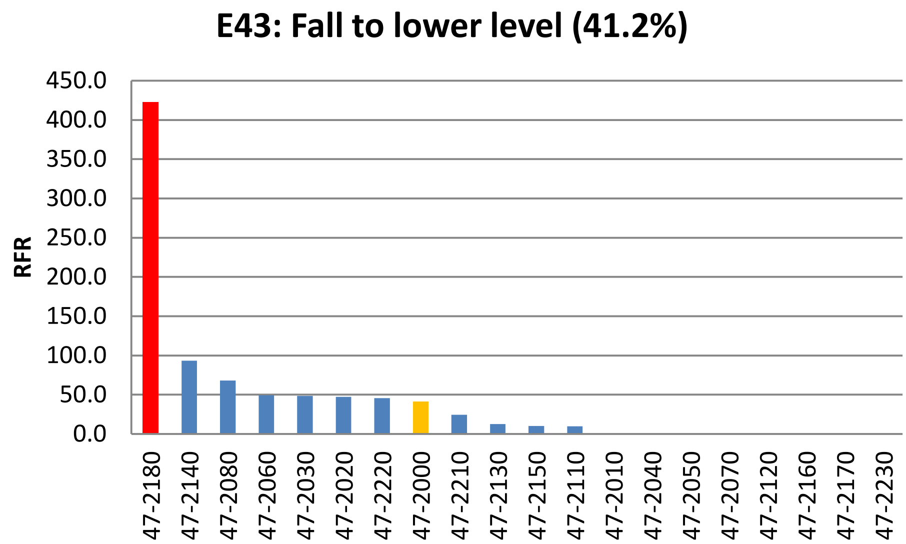



Figure 17: RFR of 'Fall to lower level' (E43) by different construction trades

As shown in Figure 17, safety mangers have to mainly consider roofers (47-2180) when they prepare a safety plan or training related to 'Fall to lower level' (E43). In a similar manner, safety materials related to specific sources or risk scenarios also can be prepared using relative injury rates data of selected sources of injury or risk scenarios.

### 3.6 CONCLUSIONS

This chapter presents an innovative safety risk quantification model to assess safety risk of different construction occupations. Based on two national safety databases, the BLS CFOI and SOII, historical accidents in 2013 were quantitatively analyzed to understand specific risk types, sources of injury, and risk scenarios associated with two different injury severities, fatality and days away injury, by 17 different construction occupations as well as overall construction trade workers.

Unlike earlier studies using qualitative inputs from experts or observational inputs from case studies, the proposed model used overall construction industry accident data to estimate safety risk in a more objective manner. It also combines two main safety attributes which are risk types and primary sources of injury to explain common accident scenarios by different construction occupations.

If safety risks are predictable, they may be prevented. Therefore, knowing the dynamic value of risk can potentially aid safety managers as well as project managers to identify the high-risk occupations or activities in advance and would enable them to prepare and allocate limited safety resources in a more efficient manner. As Apostolakis (2004) pointed out, any risk quantification model is not perfect, yet the proposed risk quantification model is expected to help upper level project managers in safety decision making to minimize safety risks in a project. Due to the limited data, the proposed risk quantification model analyzed only two types of low frequency and high impact accidents data. Future studies should integrate high frequency and low impact safety data such as near-misses to further expand the analyses.

# Chapter 4 4D Construction Safety Planning: Site-specific Temporal and Spatial Information Integration

This chapter presents a formalized 4-dimensional (4D) construction safety planning process that addresses site-specific temporal and spatial safety information. The safety data, which includes activity risk, site-specific temporal and spatial information, will be integrated from the results of Chapter 3, a project schedule, and a 3D model, respectively. The proposed safety planning approach can provide safety personnel with a site-specific proactive safety planning tool that can be used to better manage jobsite safety. In addition, visual safety materials can also aid in training workers on safety and, consequently, being able to identify site-specific hazards and respond to them more effectively.

## 4.1 INTRODUCTION

Construction remains one of most hazardous industry especially due to the dynamic nature of work environments (Bobick 2004). According to the Bureau of Labor Statistics, in 2013, 828 construction workers were killed, which represents 18.1% of fatal work injuries in the United States (BLS 2013). 828 fatalities indicate that the fatal work injury rate is 9.7 for every 100,000 full-time equivalent construction workers, and United States (US) construction workers are approximately 2.94 times more likely to be killed compared to the average fatal work injury rate for all industries, which is 3.3.

Since the Occupational Safety and Health Act of 1970 was established, which places the responsibility of construction safety on the employer, fatality and disabling rate in the construction industry has dramatically decreased. After this federal law came into effect, various injury prevention strategies have been developed and resulted in a significant improvement of safety management in the construction industry (Esmaeili and

Hallowell 2011). However, during the last decade, construction safety improvement has decelerated and fatality rate in the construction industry is still much higher than other industries (BLS 2013). As a result, innovative injury prevention practices such as integration of project schedules and information technology have been introduced to improve current construction safety management practices.

Construction safety management activities are typically categorized into safety planning and execution processes. The main tasks of safety planning include hazard identification, risk assessment, and preparing safety controls based on regulations, company safety policies, and previous experience. Safety execution process includes safety meetings/training, safety monitoring, and audits. As identified in Chapter 1.2.2, despite the interdependent relationship between safety planning and execution processes, current safety planning practices lack a systematic approach to effectively identify and manage hazards prior to construction because of limited safety tools and the dynamic nature of construction. Also, current safety planning activities lack site-specific information and, when general safety plans are used as safety materials, safety meetings/trainings are less effective and result in workers not being able to identify site-specific hazards and respond to them effectively. Due to ineffective safety planning, safety planning and execution processes are generally segregated and, consequently, most safety execution processes rely on ad-hoc safety activities during construction. Given that the majority of hazards are generated from specific site conditions and activities in construction work zones, developing site-specific safety plans is fundamental in order to improve the safety execution process and, consequently, site-specific safety management at the jobsite.

To address the safety issues related to the dynamic nature of the construction industry, Yi and Langford (2006) emphasize the importance of integration between safety management and scheduling. Hazardous situations vary according to different project progress and the schedule should be considered for safety planning (Yi and Langford 2006). However, current safety planning approaches do not consider frequent updates of a project schedule to address dynamic changes of expected hazards and safety controls. In order to create more effective site-specific safety plans, it is important to integrate safety plans and project schedules.

Another challenge of site-specific safety planning is lack of safety sources utilized. While information technology-based approaches, such as Building Information Modeling (BIM), have been widely used for project planning and progress monitoring, construction safety planning is still highly dependent on traditional sources such as 2D drawings, paper-based regulations, and tacit information. As a result, current safety planning approaches limit the capability to identify and analyze hazards prior to construction and can potentially be improved by leveraging information technology.

This chapter proposes a formalized framework for construction safety planning through a 4-dimemsional (4D) environment, which integrates 3D and time, to address site-specific temporal and spatial safety information. The proposed safety planning approach includes: (1) activity safety quantification, (2) safety schedule, and (3) safety 4D simulation.

## 4.2 BACKGROUND RESEARCH

### 4.2.1 Risk Analysis

One of main purposes of safety planning is to predict risky activities to prepare or mitigate risks in advance. Risk analysis is a systematic process to analyze systems by identifying and evaluating safety characteristics (Harms-Ringdahl 2004). In the construction industry, safety risk analysis studies can be classified into four areas:

project-, trade-, or activity-, attribute-, or worker-based risk analysis. Sun et al. (2008) assessed the risky level of Beijing Olympic venues' construction projects, and Baradan and Usmen (2006) compared riskiness of 16 construction trades. Project- and trade-based risk analyses enable the comparison of high level safety risk, but are difficult to be integrated with a project schedule which typically includes activity-based information. There have been several studies to analyze safety risk at an activity level. For example, Everett (1999) quantified construction ergonomic risks for 65 construction activities by using ordinal scoring system (1-3) obtained from expert judgement. Jannadi and Almishari (2003) developed a risk assessor model (RAM) to estimate activity safety scores using a function of severity, exposure, and probability, which was determined by end-users. Lee and Halpin (2003) identified three critical risk factors (preplanning, training, and supervision) and applied a fuzzy logic model to predict riskiness of activities related to utility-trenching process. To minimize biases inherent in a survey approach, Hallowell and Gambatese (2009) quantified safety scores of 13 activities by considering the average of severity and frequency obtained from Delphi method. The activity-based risks analysis can be integrated with a project schedule, but it is impractical and time-consuming to analyze safety scores of all construction activities using current approaches (Esmaeili et al. 2015a). Esmaeili et al. (2015b) identified and quantified safety scores of measurable attributes for struck-by hazards in the construction industry. According to this attribute-based risk analysis, safety scores of any activities can be quantified from the combination of predefined attributes and enables one to address the dynamic nature of a construction activity with safety attributes being selected by users depending on the work environment of an activity. In Chapter 3, I quantified dynamic safety risk of a worker by occupation types and predictable sources of injury. I developed safety risk quantification models for 17 different construction occupations and emphasized how differently the same sources of injury could impact on safety risk of a worker by occupation types.

Literature shows that current activity-based risk approaches have extensibility issues to be integrated with a project schedule and cannot address the dynamic nature of construction work environments. Current attribute- and worker-based risk quantification approaches can address the dynamic nature of the construction industry and be extended to estimate risks of any activities. In this chapter, the worker-based risk analysis approach developed in Chapter 3 was adapted to estimated activity risk.

### 4.2.2 Construction Safety and Schedule Integration

Construction projects are dynamic in nature (Bobick 2004); unique factors include frequent work team rotation, weather, changes in topography, and different concurrent activities including various combination of workers and equipment (Rozenfeld et al. 2010). Due to the dynamic characteristics of construction sites, the construction schedule gained attention when combined with safety planning. Two main safety sources, safety regulations and risk data, have been integrated with a project schedule. Kartam (1997) attempted to integrate the Occupational Safety and Health Administration (OSHA) regulations into schedules. Cagno et al. (2001) and Saurin et al. (2004) attempted to link construction activities in the schedule with safety control measures prepared by safety experts. The main objective of integrating safety risk data into project schedules is to identify high risk work periods and minimize possible risks in the identified periods prior to the start of the activities. Akinci et al. (2002) showed the possibility of automatically detecting and avoiding hazardous situations by integrating the project schedule into her time-space conflict analysis tool. Wang et al. (2006) attempted to identify high risk periods by integrating activities and expected injury cost data in a simulation-based model (SimSAFE). Yi and Langford (2006) stated that hazardous situations vary according to different project progress and the schedule should be considered. To address this issue, Yi and Langford (2006) attempted to predict when and where risky situations would occur by combining historical accident sources. Navon and Kolton (2006) introduced an automated safety monitoring and control model to identify fall hazards and possible locations. Hallowell et al. (2011) considered task interaction risks and suggested an integrated model of safety risk data into project schedules. Later, Esmaeili and Hallowell (2012) developed a more practical integration model by identifying common highway construction work tasks and quantifying risks of tasks in the schedule. There are also several attempts to integrate safety and schedule using different types of information technology, discussed subsequently.

Previous studies emphasized the importance of safety and schedule integration to address when and where hazards are expected using third party applications. However, there are few studies addressing how safety knowledge is dynamically updated as a project schedule is updated. Since a project schedule is frequently updated, this study will focus on the dynamic linkage of safety risk data and schedule integration.

### 4.2.3 Construction Safety and Information Technology

According to Esmaeili and Hallowell (2012), the construction industry is saturated by safety innovations and new injury prevention practices, such as integrating information technologies to construction safety, need to be introduced to improve construction safety. Since traditional 2D drawings and paper-based sources for safety planning limit the capability to identify and analyze hazards prior to construction, information technology-based approaches, such as Building Information Modeling (BIM), Geographic Information System (GIS), Augmented Reality (AR), and Sensing and Warning Technologies, have been widely studied. In the Architecture, Engineering and Construction (AEC) industry, BIM has been widely used for project planning, designing, scheduling, and estimating. Related to safety, BIM has been studied in two main aspects, 4D visualization and application of rule sets. Using 4D visualization enhances the detection of spatial conflict or congestion prior to construction (Leite et al. 2011; Mallasi and Dawood 2004). In addition, 4D simulation can overcome the problem due to the conventional safety planning practice using 2D drawings and helps safety personnel detect and analyze hazards effectively (Chantawit et al. 2005). A series of studies (Rozenfeld et al. 2009; Rozenfeld et al. 2010; Sacks et al. 2009) developed a spatial and temporal safety/schedule integration model in a 4D environment. Their preconstruction safety planning tool considered task interaction risk factors and used user-provided semi-automated data to analyze hazardous activities in a 4D simulation. Another attempt of BIM for safety is applying safety rule checking system to automatically detect hazards and generate corresponding safety measures (Benjaoran and Bhokha 2010; Zhang et al. 2013).

GIS for safety planning emphasizes that topography information can play an important role to prevent construction site accidents (Isikdag et al. 2008). Bansal (2011) integrated 4D modeling and geospatial data for construction safety in the GIS environment to predict potential hazardous places and activities.

Virtual reality (VR) has been mainly used for site safety training purposes with other visualization technologies. Hadikusumo and Rowlinson (2002) developed a design-for-safety-process (DFSP) tool to identify safety hazards generated during the design phase by integrating a virtual construction environment and a safety database. The Construction Industry Institute Research Team 293 (CII 2013) introduced the System for Augmented Virtuality Environment Safety (SAVES) to educate construction workers.

According the results, there was a 27% improvement in terms of hazard identification from workers trained in the VR environment.

Sensing and Warning Technologies have been applied to avoid jobsite collisions involved with heavy construction equipment, such as tower cranes or dump trucks. Choe et al. (2014) evaluated the reliability of radar- and ultrasonic-based collision warning systems to minimize blind area around pickup and dump trucks. Tag-based wireless radio frequency identification (RFID) systems have been actively applied for the autonomous real-time jobsite monitoring to generate warnings on hazardous zones by detecting and tracking materials or workers on foot (Maalek and Sadeghpour 2013; Naticchia et al. 2013).

The literature shows that proactive safety mitigation practices are necessary to enhance construction site safety from project planning to construction execution phases. In addition, previous studies have indicated that information technology can overcome limitations in the traditional safety planning approach.

## 4.3 Research Method

Even though all safety practices are important and interrelated, this chapter focuses on improving the safety risk analysis process in pre-project safety planning. This proposed safety risk analysis framework considers the macro level of predictable dynamic contexts of project such as activity and updates to construction documents, especially project schedules, rather than dynamic changes of micro level work situations such as uncertainties of workers, equipment path, weather, or activity delays which cannot be predicted in the early stages of a project. Micro level uncertainties should be considered in the short-term based planning as well as the field of real-time jobsite monitoring and may be integrated with the macro level safety planning process. In addition, the proposed framework identified risky activity, risky work periods, and risky work zones, but specific risk controls were not be provided because the main objective of the proposed framework is to help safety experts prepare safety controls more systematically and effectively.

Motivated by challenges and limitations of current safety planning approaches and previous research efforts to improve construction safety management using information technology, this research aims to systematically formalize the safety planning process through a 4-dimensional (4D) environment, which integrates 3D and time, to address site-specific temporal and spatial safety information. The proposed risk assessment approach includes: (1) activity safety quantification, and (2) temporal information integration (safety schedule), and spatial information integration (safety 4D simulation). Figure 18 illustrates the general process of this chapter.

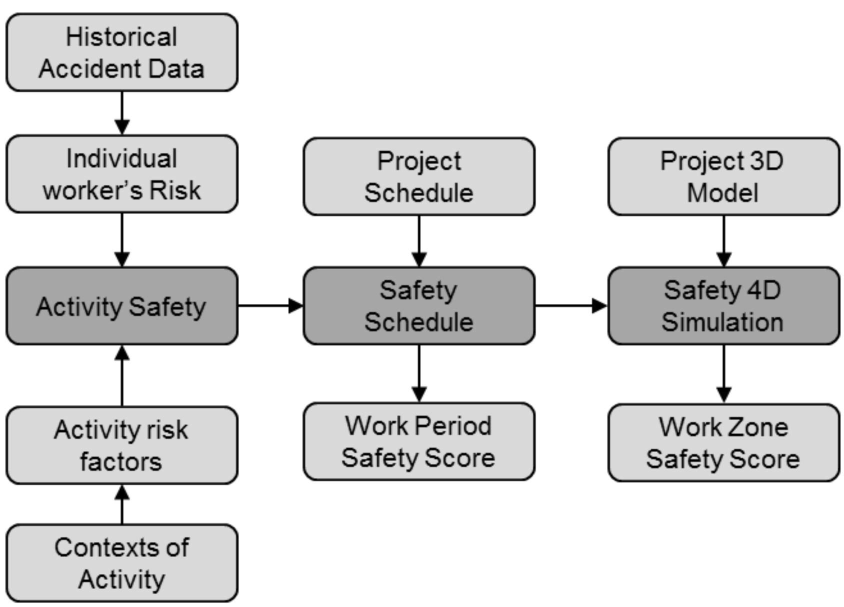



Figure 18: Three-phase general research process

As shown in Figure 18, activity safety was estimated from historical accident data (Chapter 3) and contexts of each activity. From the integration of activity safety data and project schedule, a safety schedule was generated to predict risky work period. Lastly, a safety 4D simulation was created by linking the safety schedule and a project 3D model to analyze risky work zones. Details of each process are presented in the subsequent sections.

### 4.3.1 Activity Safety Quantification

The main purpose of safety risk assessment is to estimate safety riskness of expected activities in a quantitative manner and to assist safety managers in understanding why they are dangerous prior to construction. From the quantitative safety values, risky activities can be prioritized and appropriate safety actions can be prepared when causes of riskiness are identified. In Chapter 3, individual worker's safety risk was quantified by different construction occupations and explained why they are risky based on a list of measurable activity information which can be used as a reference. However, due to the information availability at the time of analysis, activity safety can be estimated with four different scenarios as shown in Figure 19.

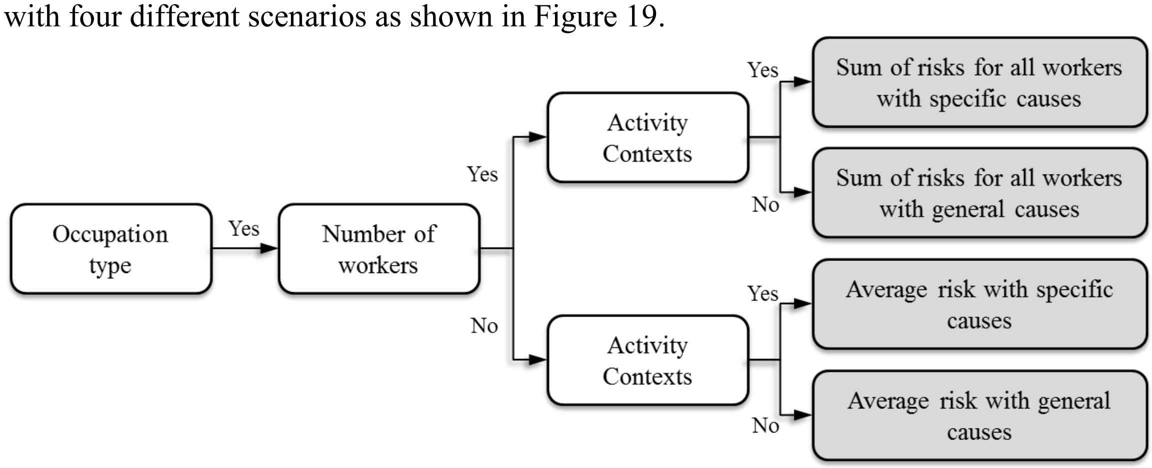



Figure 19: Four different activity safety quantification scenarios

As shown in Figure 19, the essential information of activity safety quantification is occupation type. Once occupation types are identified, the average or cumulative safety scores can be estimated based on whether the number of workers within an activity is available. In addition, depending on the availability of specific activity information such as resource or location of work, specific or general causes of activity safety can be identified. Among four activity safety quantification scenarios, the first one (i.e. sum of risks for all workers with specific causes) might be the most reliable and the last approach (i.e. average risk with general causes) might be the least reliable. In this study, a list of construction occupation types and measurable activity contexts for safety quantification were adapted from the findings in Chapter 3.

#### 4.3.2 Temporal Information Integration: safety schedule

As projects become more complex and schedule pressure increases, it has become common that multiple activities are planned at the same time. It is, thus, important to predict high risky work periods and prepare safety resources in advance. In activity safety analysis, safety score of a single activity is analyzed, while safety score of multiple activities can be analyzed by integrating project temporal information which can be extracted from a schedule. In this study, daily safety score was calculated by summing safety scores of all activities performed in a single day. The following equation shows how to calculate risk of a specific day.

$$\boldsymbol{Safety\ Score\ of\ Day\ i} = \sum_{j=0}^{n} \boldsymbol{Activity\ Safety\ Score}\ \mathbf{ij} \quad (1)$$

In which safety score of day i denotes a total safety score of day i and activity safety score ij indicates safety score of activity j planned at day i.

One of challenges of integrating activity safety score with a project schedule is frequent updates of project schedules. Therefore, work period safety score needs to be dynamically linked with a schedule to address the dynamic nature of a construction schedule. To address this challenge, activity safety score is added as a property of the activity in a schedule. As a result, safety scores are linked to activities in a schedule, and work period safety score can be estimated and updated automatically as the schedule is updated. Estimated risky work periods will be presented in a graph-based format and, thus, intuitively allow safety personnel to prepare safety resources ahead of time.

### 4.3.3 Spatial Information Integration: safety 4D simulation

According to Leite et al. (In Review), BIM has not yet been widely used for construction safety planning even though BIM is broadly used for productivity and progress monitoring. Construction safety still relies on traditional 2D drawings and paper-based sources which limits the potential capability to identify and analyze hazards prior to construction. In this research, 4D safety BIM, which integrates a safety schedule and a project 3D model, will be utilized to identify concurrent activities and predict risky work zones.

The main difference of the proposed safety 4D simulation from previous studies (Akinci et al. 2002; Sacks et al. 2009) which used existing model elements to analyze activity safety is utilizing virtual work zones to identify concurrent activities and to visualize work zone riskiness rather than utilizing actual 3D model elements. The expected advantages of using the work zone concept are: 1) safety information can be independently visualized from the original project progress information which is visualized on 3D model elements, and 2) activities which do not match the 3D model elements can be analyzed. From the use of virtual work zones linked with activities in the safety schedule, I aimed at designing dynamic work zone safety analysis which can be extensible to any activities and amplify a synergy with the original purpose of 4D simulation, project progress visualization.

The safety score of an activity can be affected by concurrent activities due to the temporal and spatial contexts of a project. Simple summation of activities' safety scores cannot fully address the safety impacts of concurrent activities because this approach does not consider dangers caused by other activities. For example, a survey activity might have little potential hazard of struck-by equipment. However, if an excavation activity is scheduled at the same time and zone as a survey activity, surveyors will be exposed to the potential hazard of being struck by an excavator or a dump truck. Therefore it is important to predict and identify concurrent activities in advance. In this research, a list of concurrent activities will be identified in the safety 4D simulation when multiple activities share the same work zone rather than quantifying amplified safety score of concurrent activities. With an identified list of concurrent activities which is also dynamically linked with a schedule update, safety personnel can provide proactive safety trainings for workers at the jobsite. After identifying concurrent activities, work zone safety score will be calculated as follows:

$$\boldsymbol{Safety\ Score\ of\ Zone\ ki} = \sum_{i=0}^{n} \boldsymbol{Activity\ Safety\ Score\ kij} \quad \textit{(2)}$$

In which safety score of zone ki denotes a total safety score of zone k at day i and activity safety score kij indicates safety score of activity j planned at day i within zone k.

### 4.4 Case Study

The purpose of the case study was to validate the proposed safety analysis approach and examine potential benefits and barriers by applying it to an actual construction project. The project B is a typical office building project located in the downtown area of a major city in Southern United States. The original plan was to start the project from March 2015, but it was initiated from August 2015 due to the owner's decision. The expected completion of the new plan is July 2017. This project consists of an underground parking garage and an office building, and the general contractor is the same company introduced in the motivating case in Chapter 1.1.2. As mentioned in the motivating case, this general contractor actively implements Building Information Modeling (BIM) for all their projects and has shown above average safety performance in the past. This project is an excellent candidate to test the proposed safety planning in following reasons:

- Due to the delay of the project initiation, the construction schedule is tighter than the original plan. There will be higher possibilities of multiple activities planned simultaneously which might increase safety risk of the jobsite.
- The project is located in a major urban area. As other typical downtown construction projects experienced, construction space is limited and the vicinity of the project is expected to be crowded. In addition, due to the focused public attention, when an undesired event such as an accident occurs in the jobsite, serious damage of the company's reputation is expected.
- The project has a zoning plan to manage their self-performing structural frame works including all formwork, rebar installation, and concrete placement. Therefore, work zone-based safety analysis can be available.
- A comprehensive project schedule, 3D and 4D models are available at the time of the case study.

Three rounds of meetings were held at the general contractor's office to share ideas and ensure successful implementation. Table 9 summarizes the purpose, participants, and focus of meeting of each meeting.

Table 9: Summary of Meetings with the General Contractor

| | 1st meeting | 2nd meeting | 3rd meeting |
|---|---|---|---|
| Purpose | Select a project<br>Define scope | Redefine scope<br>Collect feedback | Collect feedback |
| Focus of meeting | General framework | Activity analysis I<br>Safety schedule I<br>Safety 4D I | Activity analysis II<br>Safety schedule II<br>Safety 4D II |
| Participants | VDC A<br>VDC B | VDC A<br>VDC B<br>Project manager | VDC A<br>Project manager<br>Safety manager |
| Scope | N/A | Partial parking garage | Partial parking garage<br>Partial office building |
| Notes | N/A | Representative occupation | Detailed occupations and number of workers |

The initial meeting was held to share the general idea of the proposed safety planning framework. The reasons for having the meeting with VDC managers are follows; 1) the VDC managers deals with multiple projects simultaneously and, thus, the optimal project can be selected and 2) the VDC managers have important project data which are essential to develop a testbed model. After the 1st meeting, a VDC manager decided to share information of the project B since the reasons explained above, and the project B newly started which means having more potential to get benefits from the proposed safety planning than actively constructing projects. After the 1st meeting, all necessary project data including the project schedule, zoning plan, 3D and 4D models were obtained, and safety analysis was conducted for the partial underground structural frame works. In addition, the project manager provided representative occupation types for all activities scheduled during the selected period. The reason for using representative occupation types for the analysis is that the project does not have a specific number of workers and resource information for each activity.

In the second meeting, the initial activity safety analysis, safety schedule, and safety 4D simulation were reviewed with two VDC managers and the project manager.

The safety manager did not attend the meeting and the results were shared with the safety manager after the meeting. The period of safety analysis is from November 19, 2015 to December 31, 2015. During the period, six typical activities are repeated and Table 10 summarizes the results of initial activity safety score analysis.

Table 10: Summary of Initial Activity Safety Score Analysis

| Type | Representative Occupation | Activity Safety | Hazard types | | | Sources of injuries | | |
|---|---|---|---|---|---|---|---|---|
| FRP Vertical Wall | Carpenter | 196 | E43 | 48.44 | 24.7% | S65 | 22.81 | 11.6% |
| | | | E62 | 30.42 | 15.5% | S74 | 21.13 | 10.8% |
| | | | E71 | 24.77 | 12.6% | S66 | 15.48 | 7.9% |
| SOG | Laborer | 308 | E43 | 65.00 | 21.1% | S84 | 30.06 | 9.8% |
| | | | E62 | 60.44 | 19.6% | S65 | 23.79 | 7.7% |
| | | | E71 | 15.48 | 5.0% | S41 | 20.56 | 6.7% |
| FRP Column | Carpenter | 196 | E43 | 48.44 | 24.7% | S65 | 22.81 | 11.6% |
| | | | E62 | 30.42 | 15.5% | S74 | 21.13 | 10.8% |
| | | | E71 | 24.77 | 12.6% | S66 | 15.48 | 7.9% |
| Place Concrete | Laborer | 308 | E43 | 65.00 | 21.1% | S84 | 30.06 | 9.8% |
| | | | E62 | 60.44 | 19.6% | S65 | 23.79 | 7.7% |
| | | | E71 | 15.48 | 5.0% | S41 | 20.56 | 6.7% |
| Form Deck | Carpenter | 196 | E43 | 48.44 | 24.7% | S65 | 22.81 | 11.6% |
| | | | E62 | 30.42 | 15.5% | S74 | 21.13 | 10.8% |
| | | | E71 | 24.77 | 12.6% | S66 | 15.48 | 7.9% |
| Rebar/MEP Slab | Rebar workers | 166 | E71 | 48.55 | 29.2% | S41 | 41.61 | 25.1% |
| | | | E42 | 31.21 | 18.8% | S66 | 31.21 | 18.8% |
| | | | E62 | 10.4 | 6.3% | S56 | 24.28 | 14.6% |

In this analysis, safety score of an activity, hazard types, and sources of injuries are equivalent to the representative worker's occupation type. For example, Fiber-Reinforced Plastic (FRP) vertical wall has 196 safety score which is equal to safety risk of carpenter. The details of the activity safety analysis dividing results into fatality and days away injury can be found in Appendix G.

The next step is integrating a project schedule and activity safety scores to predict safety score profile throughout the selected project period. In order to update safety score profile automatically as the project changes, safety score of an activity was added as property of the activity in the schedule. During the observed period, 42 activities in total, including upper level activities, were planned on partial basements 2 and 3. Based on equation (1) presented in Chapter 4.3.2, daily safety score was estimated by summating safety scores of all activities planned at the same day. Figure 20 shows safety score profile between November 19 and December 31, 2015.

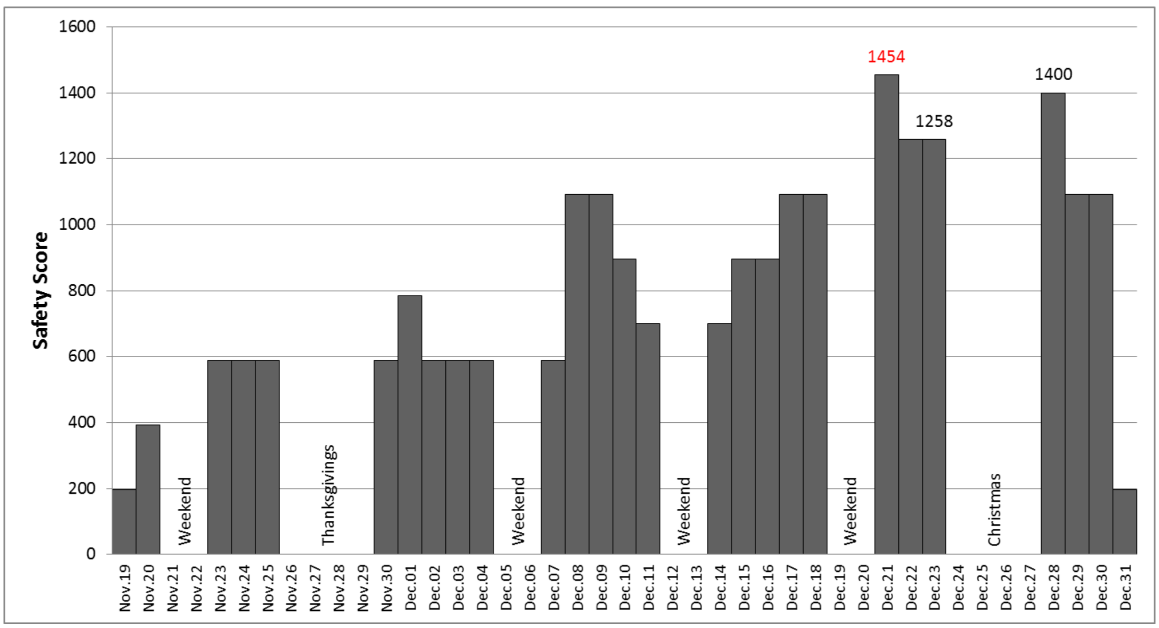



Figure 20: Initial work period safety analysis for the parking garage

In this figure, the x-axis represents amount of safety score and the y-axis indicates calendar days. Safety scores for all weekends and holidays were assumed having non-risk since no activity was planned during those days. In the initial work period analysis, December 21th was identified as the most dangerous day indicating a total safety score of 1,454. This safety score profile enables providing an overall trend of safety score fluctuation throughout a project, but still cannot explain why certain days are dangerous. Therefore, additional analysis was conducted to explain common hazard types and sources of injuries. Table 11 summarizes specific safety analysis on December 21th. More analyses can be found in Appendix G.

Table 11: Summary of Initial Safety Analysis on December 21th

| Date | Total Risk | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 1454 | FRP Vertical Walls Level B3-W7 | 196 | E43 | 362.5 | 24.9% | S65 | 143.43 | 9.9% |
| | | FRP Vertical Walls Level B3-W6 | 196 | E62 | 222.94 | 15.3% | S41 | 133.92 | 9.2% |
| | | FRP Vertical Walls Level B3-S1 | 196 | E71 | 193.61 | 13.3% | S74 | 124.44 | 8.6% |
| | | SOG Pour 2 | 308 | | | | | | |
| | | FRP Columns Level B3 (in SOG3) | 196 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 166 | | | | | | |
| | | Form Deck Level B2 Pour 1 | 196 | Representative | | 53.6% | Representative | | 27.6% |

As described in Table 11, December 21th has seven activities planned at the same day. Also, common hazard types and sources of injuries were computed based on data shown in Table 10. For example, 'Falls to lower level' (E43) and 'Other structural elements' (S65) are the most possible hazard type and source of injuries representing 21.1% and 9.9%, respectively, out of 1,454.

In the work period safety analysis, December 21th has seven activities planned at the same day which increases total safety score for that day. However, these seven activities can be either planned for the same work zone or in different work zones. Depending on the number of concurrent activities, practical safety level should be determined and different safety management controls should be required. To analyze safety riskiness by work zones, safety scores were allocated into a zone that an activity is planned for based on a zoning plan provided by the general contractor. Figure 21 shows the zoning plan for the parking garage.

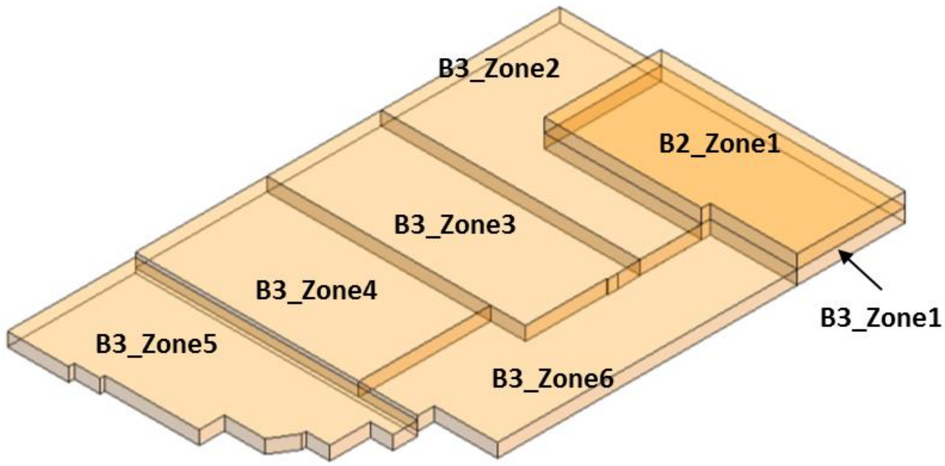



Figure 21: Zoning plan for the parking garage

During the selected period, 42 activities were planned in seven different work zones, six work zones for basement 3 and one work zone for basement 2. Figure 22 and Table 12 show overall safety score profile and specific analysis in Zone 1 of basement 3 (B3_Zone1). Work zone analysis for the rest of work zones can be found in Appendix G.

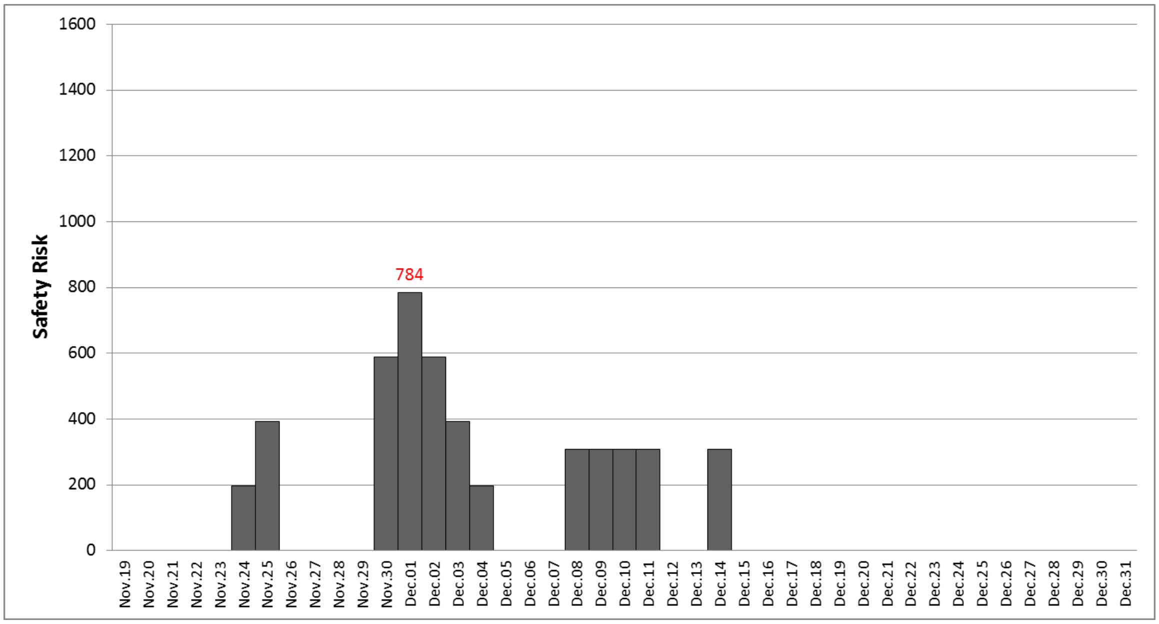



Figure 22: Initial work zone safety analysis for B3_Zone1

Table 12: Summary of Initial Safety Analysis on December 21th in B3_Zone1

| Date | Total Risk | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/1/2015 | 784 | FRP Vertical Walls Level B3-E1 | 196 | E43 | 229.68 | 29.3% | S65 | 91.24 | 11.6% |
| | | FRP Vertical Walls Level B3-N4 | 196 | E62 | 121.68 | 15.5% | S74 | 84.52 | 10.8% |
| | | FRP Vertical Walls Level B3-N3 | 196 | E71 | 99.08 | 12.6% | S63 | 66.84 | 8.5% |
| | | FRP Columns Level B3 (in SOG1) | 196 | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

As shown in Figure 22 and Table 12, December 1st is the most dangerous day of B3_Zone1 because five activities are planned simultaneously. In addition, 'Falls to lower level' (E43) and 'Other structural elements' (S65) were identified as the most critical hazard type and source of injuries indicating 29.3% and 11.6%, respectively. Using the results of work zone safety analysis, a safety 4D simulation was generated to visualize work zone safety scores. Figure 23 illustrates screen shots of the safety 4D simulation for selected dates.

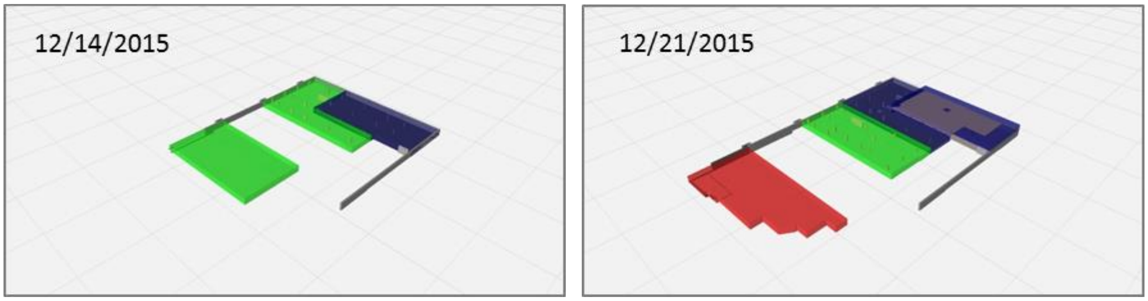



Figure 23: Examples of initial safety 4D simulation on the parking garage

In the safety 4D simulation, work zone safety scores were classified and visualized with three colors: green for low riskiness, blue for medium, and red for high riskiness. The criteria for the three levels was determined by the author, but it can be easily modified by end users.

During the 2nd meeting, all participants agreed that the number of workers should be considered for activity safety analysis. Estimating activity safety score using a representative occupation type is not reliable since some different activities such as ‘FRP Vertical Wall’, ‘FRP Column’, and ‘Form Deck’ have the same safety scores, which is not practical. According to the project manager, they used to collect the number of workers’ information from subcontractors, but nowadays this data have not been collected since they have not seen practical value in doing so. All participants agreed that using the proposed safety analysis framework would be beneficial, especially when this process is integrated with their existing safety inspection system. Also, the project manager pointed out that the safety 4D simulation can identify simultaneous activities planned for upper levels, which have identical floor plans, such as B3_Zone1 and B2_Zone1, which increase potential safety risk related to falling object hazards.

Based on feedback from the VDC managers and project manager, the activity safety analysis, safety schedule, and safety 4D simulation were updated. In the final safety analyzes, the number of workers by occupations was provided by the project manager and the partial office building sector was also analyzed. During the third meeting, VDC manager A, the project manager, and the safety manager participated in the review of the final safety analyzes.

For the parking garage, the same work period was analyzed as the initial analysis and Table 13 summarizes the final activity analysis. The details of the final activity safety analysis dividing results into fatality and days away injury can be found in Appendix I.

Table 13: Summary of Final Activity Safety Analysis for Parking Garage

| Type | Occupation | Number of workers | Activity Safety Score | Common Hazard Types | | | Common Sources of Injuires | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| FRP Vertical Wall | Carpenter | 6 | 4404.82 | E43 | 864.32 | 19.6% | S41 | 480.88 | 10.9% |
| | Rodman | 6 | | E62 | 683.48 | 15.5% | S84 | 403.46 | 9.2% |
| | Laborer | 7 | | E71 | 591.83 | 13.4% | S66 | 376.01 | 8.5% |
| | Equipment Operator | 1 | | | | | | | |
| | Total | 20 | | Representative | | 48.6% | Representative | | 28.6% |
| SOG | Carpenter | 4 | 4493.92 | E71 | 767.28 | 17.1% | S41 | 472.42 | 10.5% |
| | Rodman | 6 | | E43 | 686.88 | 15.3% | S56 | 335.94 | 7.5% |
| | Laborer | 6 | | E62 | 637.2 | 14.2% | S84 | 335.88 | 7.5% |
| | Concrete Finisher | 12 | | | | | | | |
| | Equipment Operator | 2 | | | | | | | |
| | Total | 30 | | Representative | | 46.5% | Representative | | 25.5% |
| FRP Column | Carpenter | 2 | 2362.92 | E43 | 418.84 | 17.7% | S41 | 278.58 | 11.8% |
| | Rodman | 4 | | E62 | 359.68 | 15.2% | S84 | 212.17 | 9.0% |
| | Laborer | 4 | | E71 | 332.02 | 14.1% | S66 | 211.8 | 9.0% |
| | Equipment Operator | 1 | | | | | | | |
| | Total | 11 | | Representative | | 47.0% | Representative | | 29.7% |
| Place Concrete | Carpenter | 3 | 6254.83 | E43 | 1214.66 | 19.4% | S84 | 757.58 | 12.1% |
| | Laborer | 16 | | E62 | 1093.62 | 17.5% | S65 | 538.51 | 8.6% |
| | Concrete Finisher | 4 | | E71 | 498.03 | 8.0% | S41 | 386.41 | 6.2% |
| | Equipment Operator | 1 | | | | | | | |
| | Total | 24 | | Representative | | 44.9% | Representative | | 26.9% |
| Form Deck | Carpenter | 16 | 4374.32 | E43 | 1174.62 | 26.9% | S65 | 482.48 | 11.0% |
| | Laborer | 4 | | E71 | 864.87 | 19.8% | S74 | 413.24 | 9.4% |
| | | | | E42 | 555.57 | 12.7% | S84 | 411.32 | 9.4% |
| | | | | | | | | | |
| | Total | 20 | | Representative | | 59.3% | Representative | | 29.9% |
| Rebar/MEP Slab | Rodman | 15 | 3409.57 | E71 | 855.81 | 25.1% | S41 | 693.46 | 20.3% |
| | Electrician | 3 | | E42 | 515.96 | 15.1% | S66 | 526.19 | 15.4% |
| | Plumber | 2 | | E62 | 467.1 | 13.7% | S56 | 416.41 | 12.2% |
| | | | | | | | | | |
| | Total | 20 | | Representative | | 53.9% | Representative | | 48.0% |

As can be seen in Table 13, when the number of workers was determined, more practical activity safety analysis was available. Unlike the initial activity safety analysis, safety scores of all activities are different, and common hazard types and sources of injuries are diverse by activity types. In this analysis, 'Place Concrete' was identified as the most dangerous activity since a total of 24 workers, including 16 laborers, one of the most dangerous occupation type, were expected to participate in this activity.

Figure 24 shows the final work period safety analysis for the parking garage which integrated the project schedule with updated activity safety information.

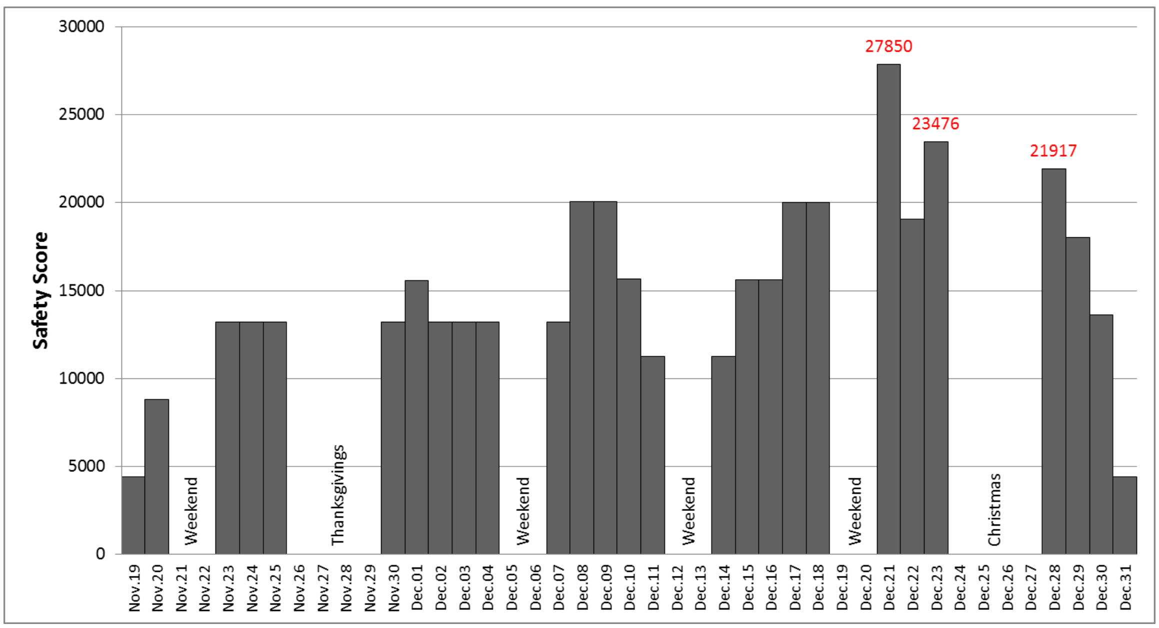



Figure 24: Final work period safety analysis for the parking garage

In the final work period safety analysis, December 21th was also identified as the most dangerous day having a total safety score of 27,850. Comparing the trend of initial work period analysis, the updated trend shows a similar safety score fluctuation as the initial safety trend before December 21th. This is because most activities prior to

December 21th are ‘FRP vertical walls’ constructions at different work zones, which resulted in similar trends between two analyses. However, after December 21th where different activity types are planned simultaneously, safety score fluctuations are quite different between two analyses. Table 14 summarizes specific safety analysis for December 21th. More analyses can be found in Appendix I.

Table 14: Summary of Final Safety Analysis on December 21th

| Date | Safety Score | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 27850 | FRP Vertical Walls Level B3-W7 | 4404 | E43 | 5135.45 | 18.4% | S41 | 3198.94 | 11.5% |
| | | FRP Vertical Walls Level B3-W6 | 4404 | E62 | 4242.9 | 15.2% | S66 | 2501.46 | 9.0% |
| | | FRP Vertical Walls Level B3-S1 | 4404 | E71 | 4211.76 | 15.1% | S84 | 2261.12 | 8.1% |
| | | SOG Pour 2 | 4493 | | | | | | |
| | | FRP Columns Level B3 (in SOG3) | 2362 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 3409 | | | | | | |
| | | Form Deck Level B2 Pour 1 | 4374 | | | 48.8% | | | 28.6% |

As described in Table 14, December 21th shows a total safety score of 27,850 and has seven activities planned for that day. Also, ‘Falls to lower level’ (E43) and ‘Building materials—solid elements’ (S41) are the most possible hazard type and source of injuries representing 18.4% and 11.5%, respectively. Compared to the results of initial safety analysis on the same day, the top three hazard types are the same with slightly different probabilities, but the top three sources of injuries are quite different.

Figure 25 and Table 15 show the final safety score profile for B3_Zone1 and specific analysis on the most dangerous day. Work zone analysis for the rest of work zones can be found in Appendix I.

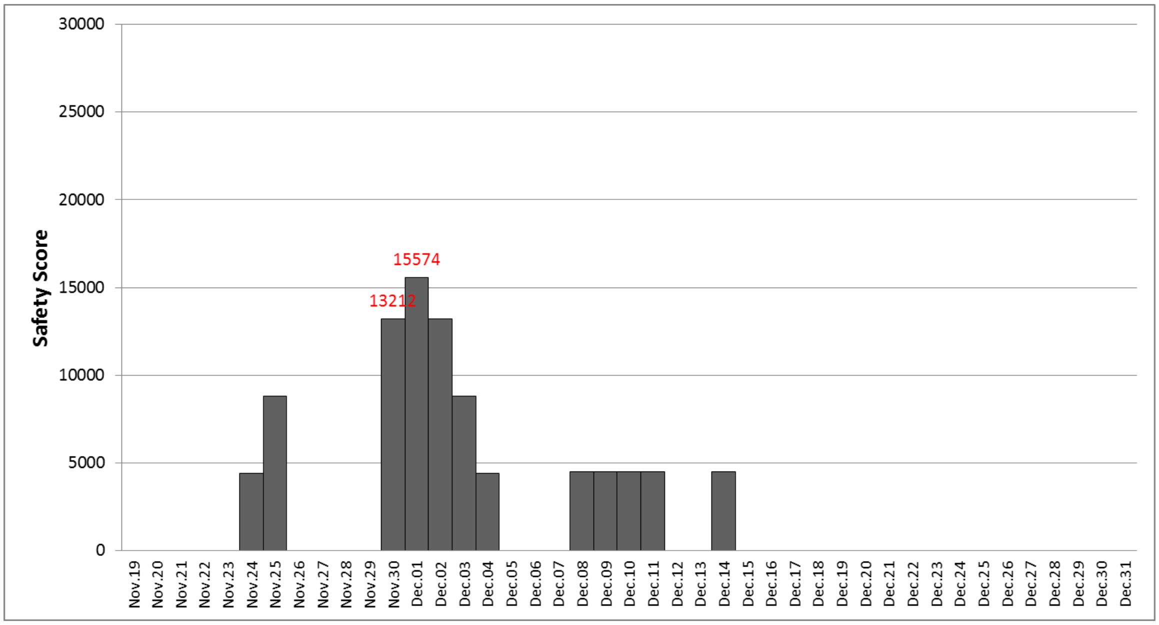



Figure 25: Final work zone safety analysis for B3_Zone1

Table 15: Summary of Final Safety Analysis on December 21th in B3_Zone1

| Date | Safety Score | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/1/2015 | 15574 | FRP Vertical Walls Level B3-E1 | 4404 | E43 | 3011.8 | 19.3% | S41 | 1721.22 | 11.1% |
| | | FRP Vertical Walls Level B3-N4 | 4404 | E62 | 2410.12 | 15.5% | S84 | 1422.55 | 9.1% |
| | | FRP Vertical Walls Level B3-N3 | 4404 | E71 | 2107.51 | 13.5% | S66 | 1339.83 | 8.6% |
| | | FRP Columns Level B3 (in SOG1) | 2362 | | | | | | |
| | | | | | | 48.3% | | | 28.8% |

As shown in Figure 25 and Table 15, December 1st is the most dangerous day of B3_Zone1 as the same as the results of the initial analysis. ‘Falls to lower level’ (E43) and ‘Building materials—solid elements’ (S41) were identified the most critical hazard type and source of injuries indicating 19.3% and 11.1%, respectively. Compared to the results of initial safety analysis in the same work zone, the top three hazard types are the same with slightly different probabilities, but the top three sources of injuries are quite different. This result is similar to the comparison between the results of two versions work period analysis. With updated work zone safety information, the final safety 4D simulation for the parking garage was generated and Figure 26 shows two screen shots of the final safety 4D simulation on the same dates used in Figure 23. Additional screen shots are shown in Appendix I.

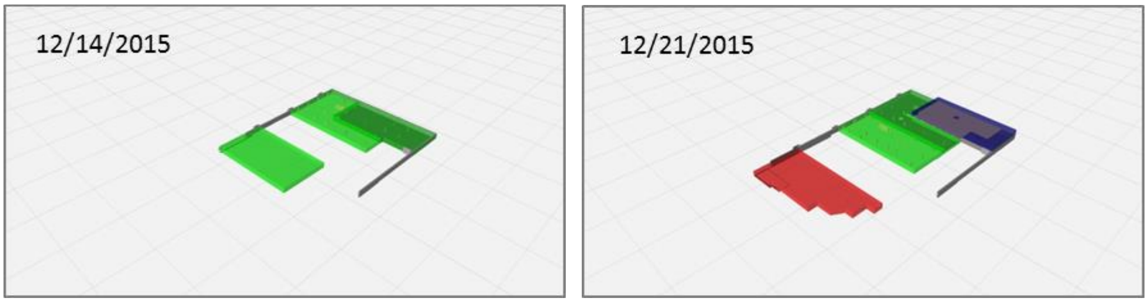



Figure 26: Examples of final safety 4D simulation on the parking garage

During the review of the final safety analysis for the parking garage, all participants agreed that the result of the final activity safety analysis was more feasible and, consequently, the following final work period and zone analysis became more reliable. One issue related to the level of detail of the activities in the schedule was pointed out by the project manager. In the project schedule, the levels of detail for the activities are not consistent. For example, floor construction is divided into ‘Form deck’, ‘Rebar/MEP slab’, and ‘Place concrete’ while wall construction is not divided into detailed activities as floor construction. This inconsistency of activity tasks resulted in overestimation of safety score of ‘FRP vertical wall’ activities. For example, three ‘FRP vertical walls’ activities are planned in B3-Zone1 on December 1$^{st}$ (see Table 15), and each vertical wall activity are assumed as having six carpenters, six rodmen, seven laborers, and one equipment operator. However, in reality, six carpenters and two laborers will work on ‘FRP Vertical Walls Level B3-N3’ to install forms, six rodmen will install rebar in ‘FRP Vertical Walls Level B3-N4’, and three laborers and one equipment operator will place concrete on ‘FRP Vertical Walls Level B3-E1’. That means safety scores of three activities should be equal to safety score of one activity on December 21th since each vertical wall construction activity has different sub tasks. All participants in the meeting agreed that more reliable safety analysis can be implemented if activities in the schedule are detailed.

In the third meeting, safety analysis for part of the office building was also reviewed. The period of this safety analysis is from August 11, 2016 to September 23, 2016. During the period, four typical activities were analyzed and Table 16 summarizes the results of activity safety analysis.

Table 16: Summary of Activity Safety Analysis for Office Building

| Type | Occupation | Number of workers | Activity Safety | Common hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| Form Deck | Carpenter | 21 | 6895.17 | E43 | 1790.82 | 26.0% | S65 | 743.43 | 10.8% |
| | Laborer | 9 | | E62 | 1182.78 | 17.2% | S84 | 705.72 | 10.2% |
| | | | | E71 | 711.06 | 10.3% | S74 | 612.84 | 8.9% |
| | | | | | | | | | |
| | Total | 30 | | Representative | | 53.4% | Representative | | 29.9% |
| FRP Vertical Concrete Column | Carpenter | 2 | 2030 | E43 | 398.04 | 19.6% | S84 | 212.17 | 10.5% |
| | Rodman | 2 | | E62 | 338.88 | 16.7% | S41 | 195.36 | 9.6% |
| | Laborer | 4 | | E71 | 234.92 | 11.6% | S65 | 163.14 | 8.0% |
| | Equipment Operator | 1 | | | | | | | |
| | Total | 9 | | Representative | | 47.9% | Representative | | 28.1% |
| Rebar/MEP Slab | Rodman | 15 | 3409.57 | E71 | 855.81 | 25.1% | S41 | 693.46 | 20.3% |
| | Electrician | 3 | | E42 | 515.96 | 15.1% | S66 | 526.19 | 15.4% |
| | Plumber | 2 | | E62 | 467.1 | 13.7% | S56 | 416.41 | 12.2% |
| | | | | | | | | | |
| | Total | 20 | | Representative | | 53.9% | Representative | | 48.0% |
| Place Concrete | Carpenter | 4 | 2818.16 | E71 | 489.83 | 17.4% | S32 | 209.38 | 7.4% |
| | Laborer | 3 | | E43 | 427.08 | 15.2% | S84 | 197.24 | 7.0% |
| | Concrete Finisher | 16 | | E62 | 397.84 | 14.1% | S65 | 179.38 | 6.4% |
| | Equipment Operator | 1 | | | | | | | |
| | Total | 24 | | Representative | | 46.7% | Representative | | 20.8% |

Common activity types are similar to ones analyzed in the final activity safety analysis for the parking garage, but the number of workers by occupations is different and, thus, safety score of the same activity type in the office building is different from the one from the parking garage. For example, in the parking garage, the safety score of ‘Form deck’ was 4,374 with 16 carpenters and four laborers while ‘Form deck’ activity in the office building has 21 carpenters and nine laborers resulting in the safety risk score of 6,895.

Figure 27 shows the work period safety analysis for the building office.

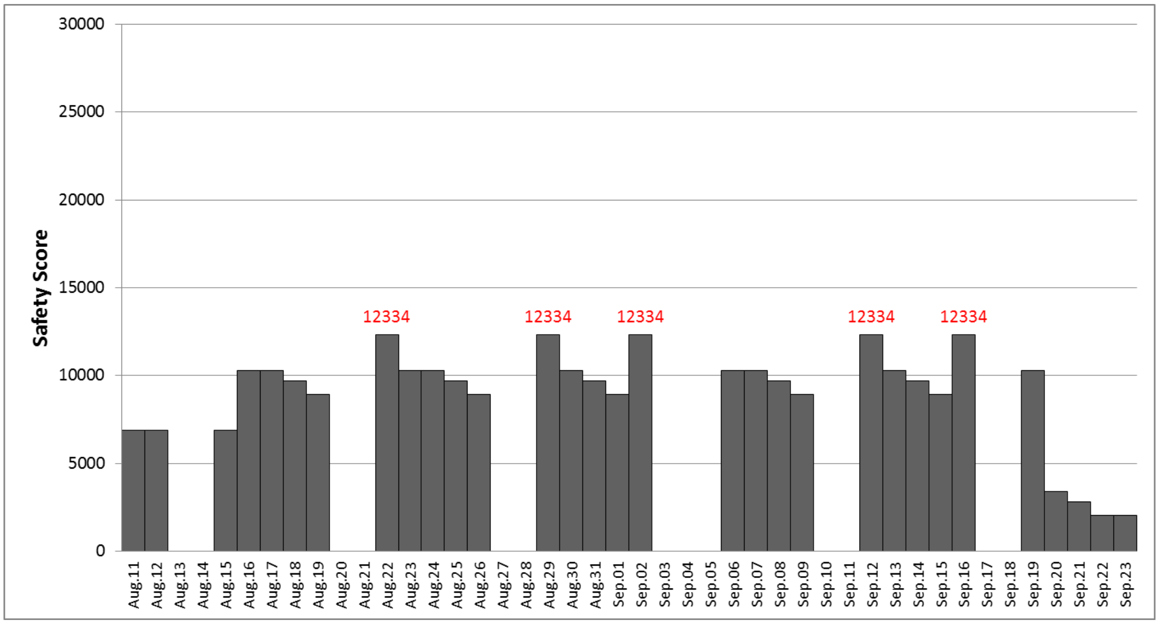



Figure 27: Work period safety analysis for the office building

In the work period analysis, five dates, August 22nd, 29th and September 2nd, 12th, 16th, were identified as the most dangerous days having a total safety score of 12,334. In the office building, 'Form deck', 'Rebar/MEP slab', 'Place concrete', and 'FRP vertical concrete column' activities are repeated, and, thus, a fluctuation of safety score also repeats. Compared to the garage building, the maximum daily safety score of the building office is much lower than that of the garage building. That is because the square footage of the parking garage is much larger than the one of office building and, consequently, more activities are planned simultaneously. Table 17 summarizes specific analysis for August 22$^{nd}$, 2016. More analyses can be found in Appendix J.

Table 17: Summary of Safety Analysis on August 22nd

| Date | Safety Score | Activities | | Common hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/22/2016 | 12334 | FRP Vertical Concrete Level 6 Pour 1 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 6 Pour 2 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 6 Pour 2 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |

As analyzed in Table 17, August 22nd shows a total safety score of 12,334 and has three activities planned at that day. Also, 'Falls to lower level' (E43) and 'Building materials—solid elements' (S41) are the most possible hazard type and source of injuries representing 19.8% and 11.1%, respectively.

In order to examine the concentration of safety riskiness on work zones, work zone safety was also analyzed for the office building based on the zoning plan shown in Figure 28.

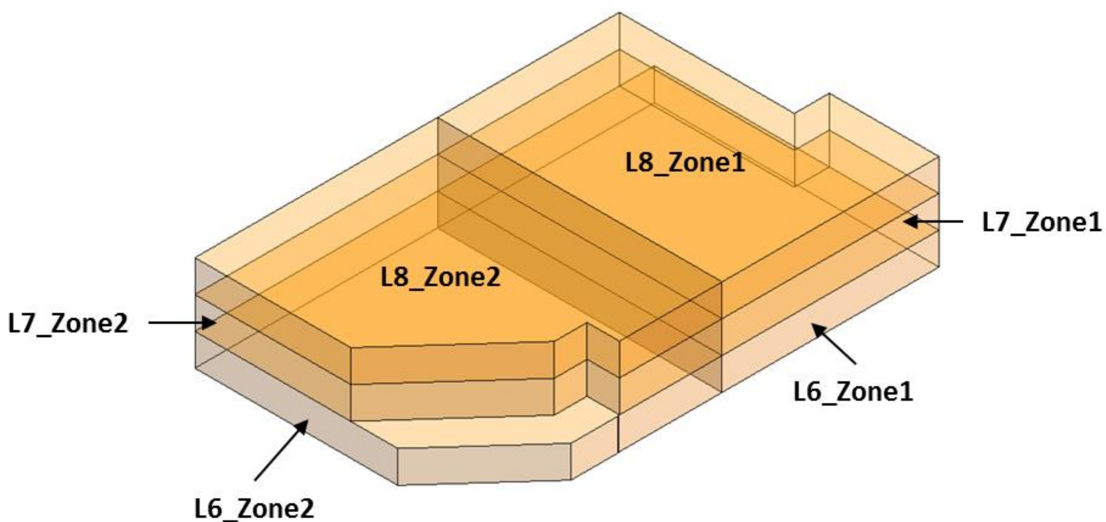



Figure 28: Zoning plan for office building

Figure 29 and Table 18 show the safety score profile in Zone 1 at Level 6 (L6_Zone1), as well as specific analysis on the most dangerous day. Work zone safety analysis for the rest of work zones can be found in Appendix J.

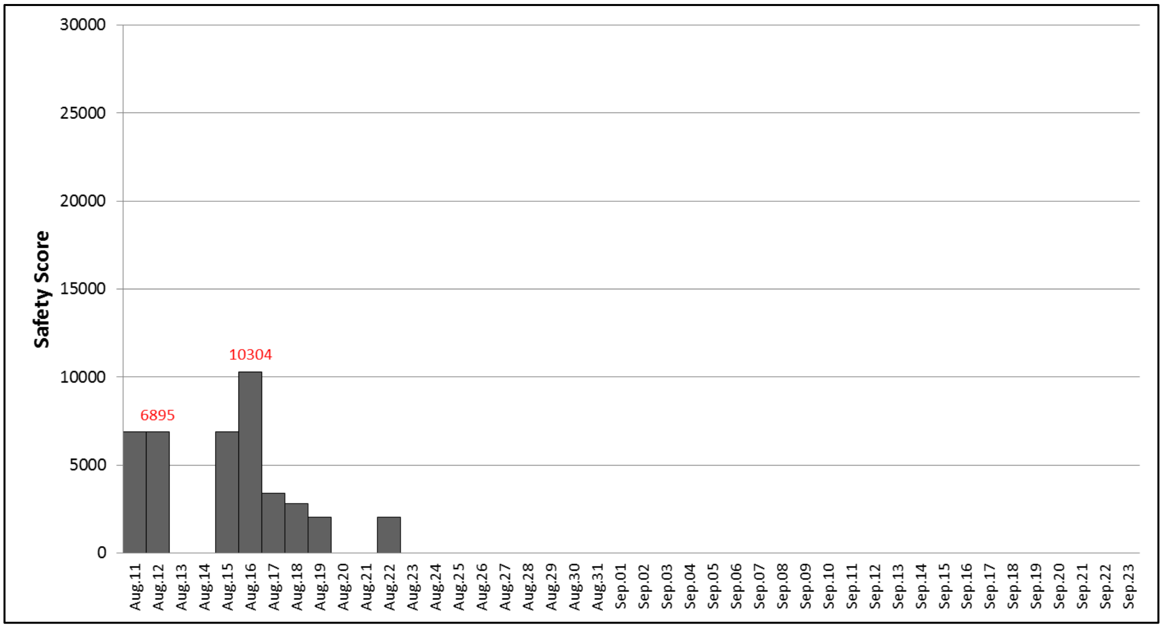



Figure 29: Work zone safety analysis for L6_Zone1

Table 18: Summary of Safety Analysis on August 16th in L6_Zone1

| Date | Safety Score | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/16/2016 | 10304 | Rebar/MEP Slab Rough Level 6 Pour 1 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 6 Pour 1 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

As shown in Figure 29 and Table 18, August 16$^{th}$ is identified as the most dangerous day of L6_Zone1 indicating two activities are planned simultaneously. ‘Falls to lower level’ (E43) and ‘Building materials—solid elements’ (S41) are identified as the most critical hazard type and source of injuries indicating 19.9% and 11.5%, respectively.

In the office building safety analysis, each work zone has a similar trend of safety score profile because the sizes of zones are similar and five activities are repeated.

Based on work zone safety information, a safety 4D simulation was generated and Figure 30 shows two screen shots of the safety 4D simulation for the office building. Additional images can be found in Appendix J.

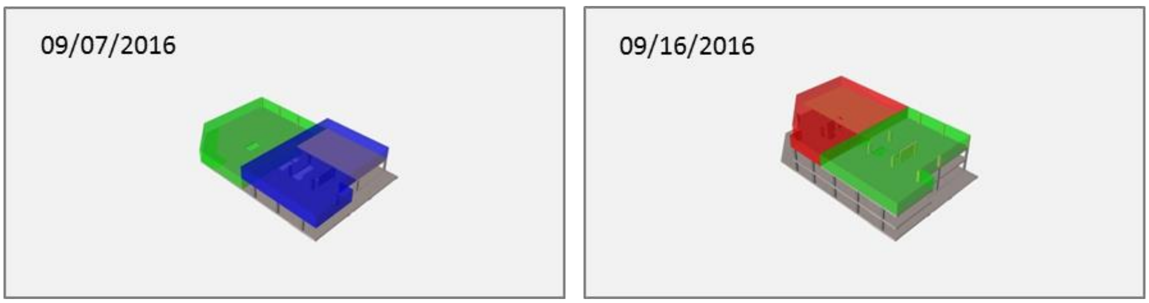



Figure 30: Examples of safety 4D simulation on the office building

As can be seen Figure 30, work zone riskiness were classified and visualized with three colors: green for low, blue for medium, and red for high risky work zones. The same criteria was used as the parking garage to determine three levels. One of main purposes to develop a safety 4D simulation for the office building was to visually identify activities planned at upper levels. However, there were no activities scheduled in a level immediately above where an activity was taking place.

### 4.5 Potential Benefits and Challenges

During the three rounds of meetings, several potential benefits and barriers were identified. Potential benefits are:

- The step-by-step safety risk analysis process helps safety managers develop a safety planning systematically. According to the safety manager, the company does not have any formalized framework for analyzing activity safety risk. Although the safety manager recognized the importance of proactive risk analysis to prepare risk controls in advance, they have difficulty analyzing them due to the lack of tools. Consequently, safety risks were only predicted on a daily- or weekly-based during the construction, based on experiential knowledge.

- The proposed safety risk analysis can explain why certain activities, days, and zones are dangerous based on historical data and a schedule, respectively. The safety manager pointed out that one of the biggest challenges he encountered was to explain why some workers will be in danger. Due to the lack of reliable data, the safety manager only attempted to instruct field workers based on his intuition, which is not effective. Since the proposed safety planning approach can provide common hazard types and sources of injuries by activities, daily, and work zones, this study has great potential to improve current tacit-based safety management.
- Long-term safety risk prediction is possible. The safety manager mentioned that current safety inspection plans are developed in the short-term, such as on a daily basis. As a result, they sometimes fail to prepare enough safety actions in advance. Using the safety profile generated from the safety schedule, the safety inspection plan can be developed in advance and adequate safety actions can be prepared.
- Visualized outcomes such as safety 4D simulation can increase safety communication among project participants. According to the project manager, most safety communication happens verbally. If all project participants can share visualized safety materials related to their works, increased safety awareness and understandings are expected.

Even though potential benefits are promising, there are several challenges to be solved.

- More automatic process is necessary. Even though daily safety and work zone safety scores can be updated dynamically as a schedule is updated, activities' safety scores should be added to the schedule manually which might be time-consuming and error-prone. Also, when a work zone plan changes, locations of all activities should be reviewed and reallocated if necessary. One of main reasons of not analyzing the entire project is that the zoning plan used in this study is supposed to be updated shortly.
- The proposed safety planning process was aimed to help safety managers analyze safety risk in a systematic manner by integrating a project schedule and 3D model. However, safety managers are not knowledgeable in generating safety schedules and 4D simulations, which require knowledge on related software. Therefore, it is necessary to train safety managers to properly obtain such skills to enable seamless integration of schedules and safety plans.

In general, the project team that participated in this research expected more potential benefits of the proposed safety planning process and promised willingly to help further this study. Once the work zone plan is updated, the safety risk of the entire project will be analyzed. In addition, the visualized outcomes will be used for safety meetings/training in the project.

### 4.5 Conclusions

Traditional safety planning approach mostly relies on tacit knowledge as well as regulations, company safety policies, and 2D drawings. As a result, site-specific temporal (e.g. when and who will be exposed to potential hazards) and spatial (e.g. location of dangerous zones) information are currently not specifically addressed in a formalized manner. To address this gap, this study proposed a formalized framework for the construction safety planning process in a 4-dimensional (4D) environment to address site-specific temporal and spatial safety information. The proposed framework analyzed work period and work zone safety by integrating an activity safety data with a project schedule and a 3D model. The proposed safety planning process was tested with a real-world project and modified based on valuable feedback from practitioners.

The proposed safety planning approach with temporal and spatial inputs can provide safety personnel with a site-specific proactive safety planning tool and the proposed macro-level site-specific safety planning framework can be integrated with micro-level safety practices such short-term based logistic plan or inspection plan to optimize jobsite safety management. In addition, visual safety materials can also aid in worker safety training and, consequently, positively impact safety communications and awareness of site-specific hazards.

# Chapter 5 Conclusions and Future Research

This research aimed at formalizing the construction safety planning process in a 4-dimensional (4D) environment to address site-specific temporal and spatial safety information. The vision of this research is that the proposed framework can be used to provide guidance for developing site-specific safety plans in a systematic manner by integrating historical accident data, project schedule and 3D model. This chapter summarizes the major conclusions and contributions of this research, as well as suggested directions for future research.

## 5.1 Conclusions and Contributions

Four key values for successful construction projects are cost, time, quality, and safety. In order to pursue these core values with satisfactory outcomes, a project team generates long-term prediction models and keeps tracking outcomes to meet the goal. Cost estimates, schedule, and drawings with specifications are long-term prediction models to optimize project budget, time, and quality, respectively. These prediction models are developed systematically. There are several reliable nation-wide references to aid in developing thorough plans such as RS Means for cost estimating, and a number of off-the-shelf software and tools that can help improve project performance. In addition, the first three core values (cost, time, and quality) are closely integrated to optimize the prediction model and obtain desired outcomes often with the aid of advanced information technologies. However, construction safety planning lacks reliable tools for developing a long-term prediction model in a systematic manner. Consequently, current construction safety management focuses more on short-term prediction models for specific activities, such as safety plans for tower crane erection and inspections during construction. In addition, due to the absence or quality of a long-term prediction model for safety, safety plans are often segregated from other core values' prediction models such as a project schedule. To overcome these challenges, this research presented a formalized framework for construction safety planning process to guide in developing long-term prediction models for safety by proposing a safety reference and a systematic process to integrate safety plans with other prediction models such as a project schedule and 3D model.

As the first step, this research proposed a safety risk generation and control model to describe the phenomenon of dynamic safety risk with construction domain knowledge. In this model, I explained the pattern of safety risk generation and mitigation with predictable project contexts such as occupation types, physical activity contexts, and temporal and spatial contexts. The model assumes that every worker has inherent risk. When an activity is assigned to a worker, his/her risk is specified based on a number of activity risk and temporal/spatial risk factors. These specified activity risks may be mitigated by safety management control, and uncontrolled risk results in undesired events. The expected contribution of the proposed risk generation and control model is to provide a theoretical background to aid in practical risk assessment methods by understanding the process of safety risk generation and mitigation.

Based on the model developed in Chapter 2, this research assesses safety risk of different construction trades in a quantitative manner. By integrating multiple national injury databases, safety risks of 17 construction occupations were quantitatively analyzed to explain common risk types, sources of injury, and risk scenarios associated with each occupation type. The findings of this assessment revealed that different occupations were exposed to different types of hazards and common sources of injuries are diverse by trades. The safety risk analysis presented in this research is expected to help project participants including safety managers understand the dynamic nature of safety risk. In addition, the results of the analysis can be used as a safety risk reference in developing site-specific safety risk analysis. Lastly, the proposed data structure can provide a direction of future data collection related to injuries as well as near misses.

This research proposes a formalized framework for a long-term risk prediction model for construction safety planning. If safety risks are predictable, they may be prevented. Therefore, knowing the dynamic value of safety risk can potentially aid safety managers as well as project managers in identifying the high-risk occupations or activities in advance and would enable them to prepare and allocate limited safety resources in a more efficient manner. Current safety planning approaches mostly rely on tacit knowledge. As a result, site-specific temporal (e.g. when and who will be exposed to potential hazards) and spatial (e.g. location of dangerous zones) information are currently not specifically addressed in a formalized manner. To address this gap, this study proposed a formalized framework for the systematic construction safety planning process in a 4-dimensional (4D) environment to address site-specific temporal and spatial safety information. The proposed framework analyzed work period and work zone safety riskiness by integrating an activity safety data with a project schedule and a 3D model. The proposed safety planning process was tested in a real-world project and modified based on valuable feedback from practitioners. The proposed safety planning approach with temporal and spatial inputs can provide safety personnel with a site-specific proactive safety planning tool. The proposed macro-level site-specific safety planning framework can be integrated with micro-level safety practices such short-term based logistic plan or inspection plan to optimize jobsite safety management. In addition, visual safety materials can also aid in worker safety training and, consequently, positively impact safety communications and awareness of site-specific hazards.

## 5.2 Future Research

Construction safety management is a promising research area, especially when integrated with advanced information and communication technologies (ITC). Directions for future research in this area are listed as follows:

(1) Integration with micro level safety planning and controls

Even though all safety practices are important and interrelated, this research focused on developing a long-term safety risk prediction model, given that subsequent safety practices can be significantly impacted by macro level plans. If micro level safety plans, such as logistics or inspection plans developed during construction are integrated, the capability of the proposed safety planning process will be further enriched. In addition, the proposed safety framework identifies risky activities, risky work periods, and risky work zones to aid safety personnel in preparing risk controls in advance in a more effective manner. If specific safety controls are integrated with the proposed framework and generated safety reports in an automatic way, the entire safety planning process will be enhanced.

(2) Development of safety risk reference by project types

The proposed safety risk reference was developed based on the entire construction injury data regardless of specific project types. However, common injury types and sources of injuries might be different by project types as well as occupation types. Therefore, analyzing safety risk by project types can provide a more reliable reference to aid safety managers in developing more practical prediction models.

(3) Automation in safety planning process

As identified challenges of the proposed safety planning approach in Chapter 4.5, automated processes are necessary for the successful implementation of this research. Even though daily safety risk and work zone risks can be updated dynamically as schedules are updated, safety risk scores should be added to the schedule manually which might be time-consuming and error-prone. Also, when a work zone plan changes, locations of all activities should be reviewed and reallocated if necessary. Therefore, there is a need to refine the proposed framework in an automated manner.

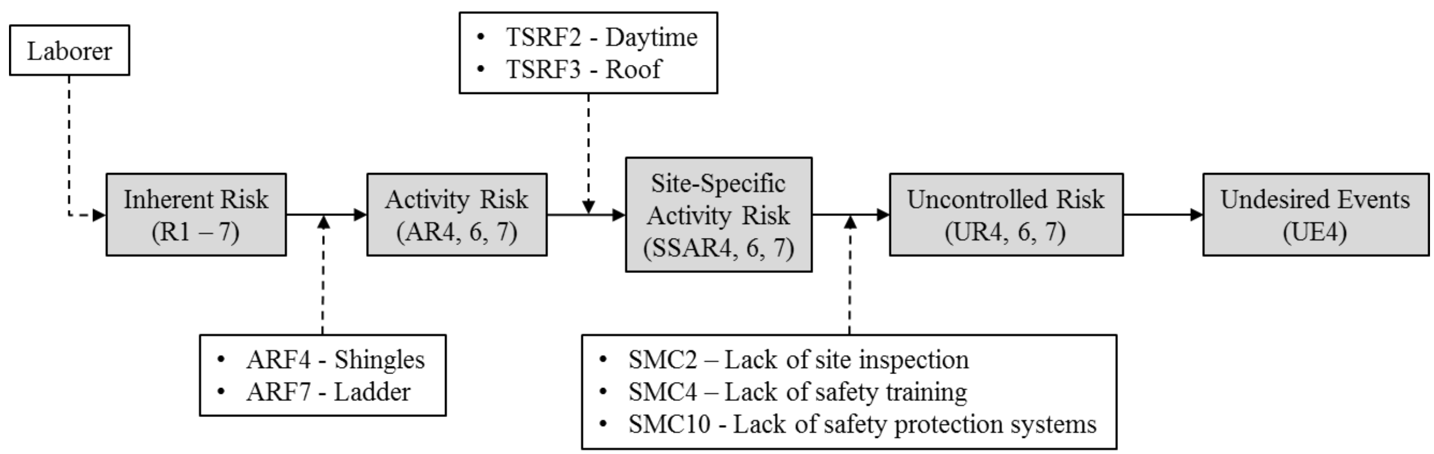
# Appendix A - Application of Risk Generation and Control Model to the NIOSH FACE Program Reports

## A.1 NIOSH FACE REPORT 2012-02

**Description**

On April 19, 2012, a 37-year-old Hispanic male laborer fell approximately 13.5 feet from a residential roof to a concrete driveway; he died immediately from his injuries. The laborer was working with a crew of eight Hispanic workers for a construction subcontractor replacing shingles on a roof accessed by a ladder. At the time of the incident, five workers were on the roof, including the laborer who was out of sight of his coworkers working on the garage side of the home. When the incident occurred, the co-workers heard the laborer hit the ground, rushed to his aid, and called 911. Emergency Medical Services were dispatched to the incident and the laborer was pronounced dead at the scene.

**Model Application**

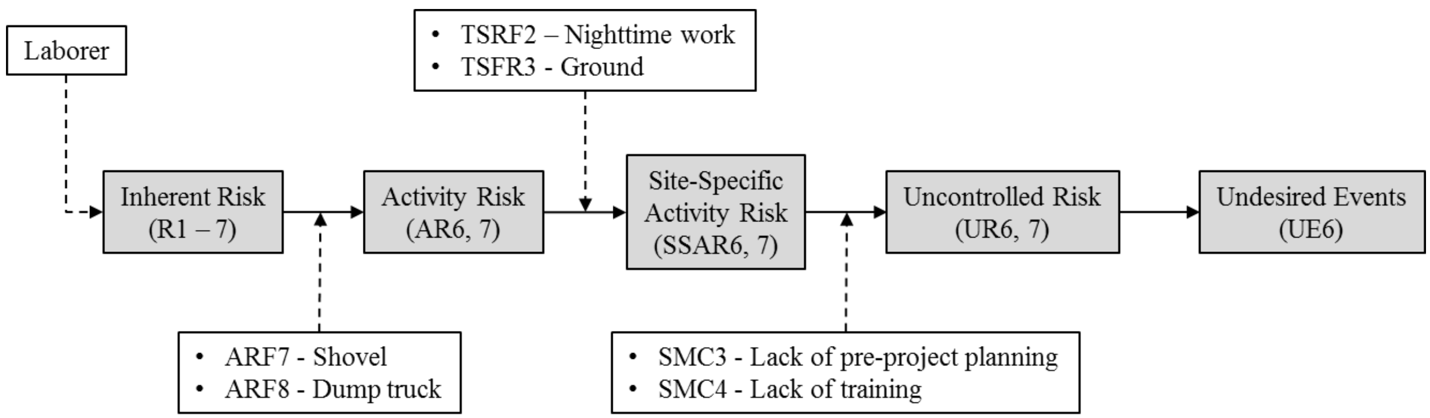


### A.2 NIOSH FACE REPORT 2006-03

Description

On July 18, 2006, a 21-year-old male road construction worker (the victim) was fatally injured when a dump truck partially loaded with asphalt backed over him. The victim was a member of a road construction crew working at night on a state highway paving project. The dump truck driver was backing through the work zone, with the truck's back up alarm sounding, toward the next section of roadway to be paved when the truck struck the victim. The paver and paving crew had already re-positioned to the next section of roadway to be paved. The dump truck driver was watching the driver's side mirror as he was backing to align the truck with the re-positioned paver. As he was backing he did not see anyone behind the truck. He then saw something appear out from under the front of the truck, at which time he stopped the truck. Evidence suggests the victim had his back to the dump truck. The victim had not been assigned tasks within the workzone, but may have been shoveling spilled asphalt. Emergency medical services (EMS) personnel were called and arrived on the scene to find the victim deceased.

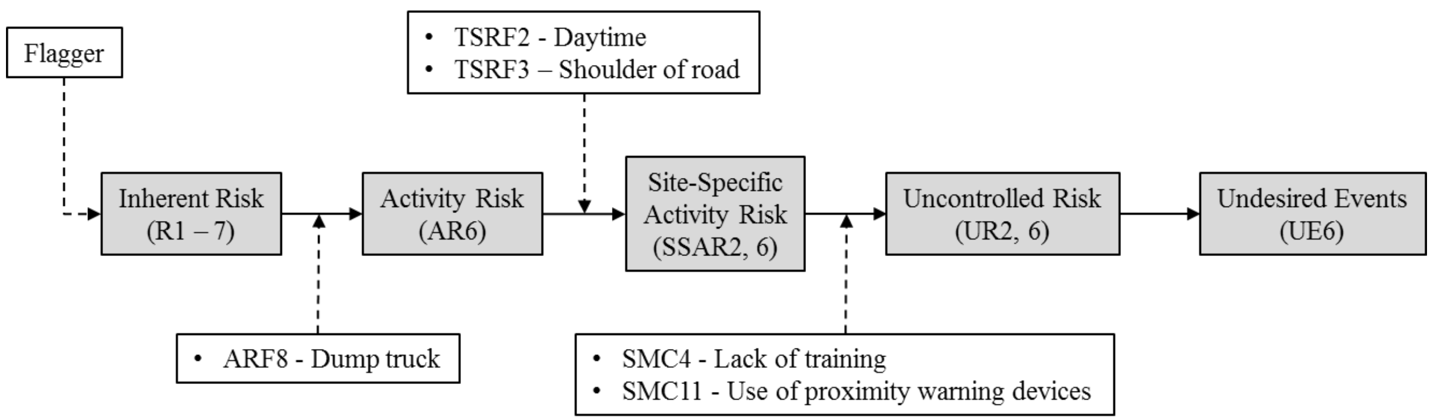
Model Application



Description

On June 29, 2004, a 34-year-old Hispanic flagger (the victim) died after being run over by a partially-filled dump truck. The victim was a member of a three-man crew filling drop-off areas along the shoulders of a secondary state road with a dirt/gravel mixture of unclassified stone, also known as UCL. The victim was flagging from a position on the passenger side of the ten-wheel dump truck, on the shoulder of the opposite side of the road. As the amount of UCL became insufficient to level the road shoulder, the driver-side worker motioned for the truck driver to stop the truck and raise the bed to allow more UCL to flow to the rear of the truck. When sufficient material to fill the low spots again began to flow, the worker motioned for the driver to pull forward. As the truck moved forward, the rear of the truck swayed and the driver-side worker again motioned the driver to stop. He then walked around the rear of the truck to the passenger side and discovered the victim underneath the two sets of rear tandem wheels. He called to the driver, who ran around the front of the truck to the passenger side and immediately called 911 from a cell phone. Emergency Medical Service (EMS) and fire personnel responded and used a jack to raise the rear axle of the truck and extricate the victim. Two emergency room physicians passing the scene stopped to assist the EMS personnel in treating the victim.

Model Application

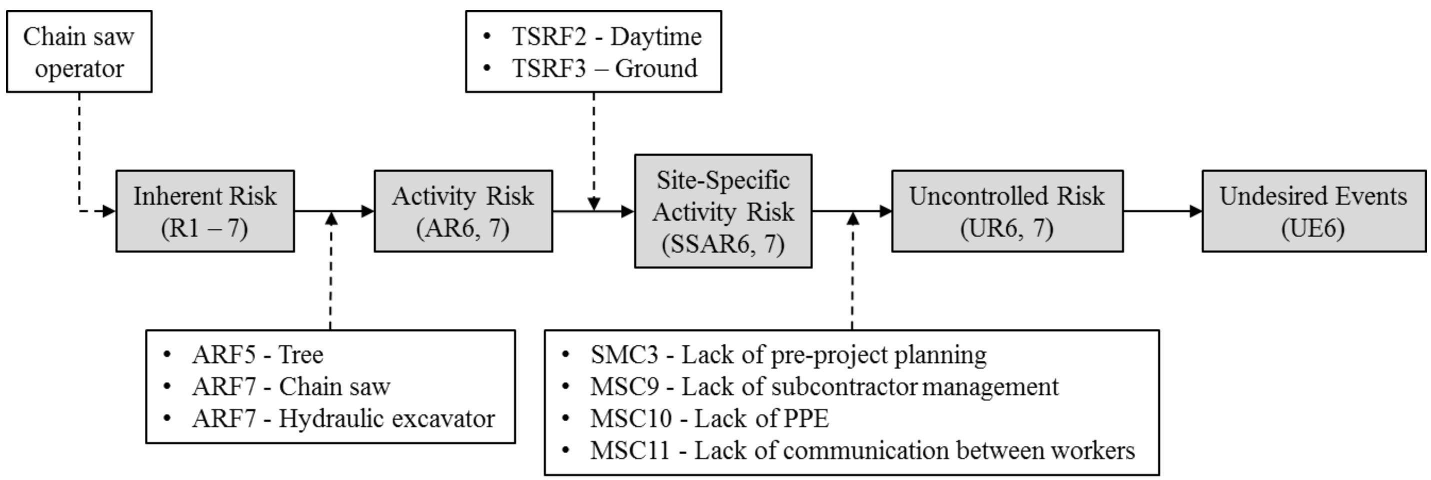


## A.4 NIOSH FACE REPORT 2004-07

**Description**

On July 27, 2004, a 46-year-old chain saw operator (victim) was cutting root balls from trees pushed over during site clearing, when he sustained fatal crushing injuries after being struck by the bucket of a track-mounted hydraulic excavator. The excavator operator was using the bucket on the excavator to push over trees, straighten downed trees for stumping, and move damaged trees to a large burn pile. When he realized he had not seen the victim for approximately 15 minutes, he moved the excavator to get a better view of the area and saw the victim on the ground. He jumped out of the excavator and ran to the victim. Unable to get a response when he called to the victim, he ran to his employer who called 911 on his cell phone. The employer drove to the main road to help emergency medical service personnel (EMS) locate the incident site. Police officers responded within minutes and the excavator operator accompanied them to the incident site. The victim was pronounced dead at the scene at 10:30 a.m. by EMS personnel.

**Model Application**

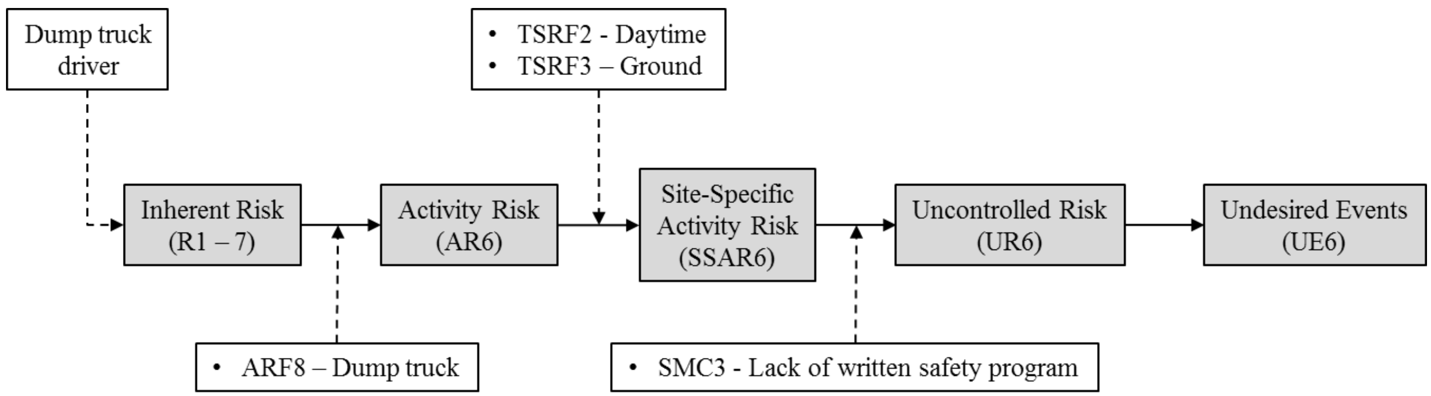


## A.5 NIOSH FACE REPORT 2002-08

Description

On June 24, 2002, a 21-year-old Hispanic dump-truck driver (the victim) died after being caught between the frame and dump body of an off-road dump truck while performing routine lubrication. The victim was working for an excavation contractor at a landfill expansion site on the day of the incident. The victim's foreman drove by the area where the company service truck was set up and stopped to investigate when he heard the air compressor running but not the usual clicking sounds made when workers are greasing their trucks. He found the victim caught between the frame and dump body of the truck. The foreman called out for help and then called 911 from his cell phone. An excavator operator working nearby responded to the foreman's call for help and climbed into the cab of the truck and raised the bed. Emergency medical services (EMS) and law enforcement personnel responded within 10 minutes. EMS personnel transported the victim by ambulance to a local hospital where he was pronounced dead.

Model Application

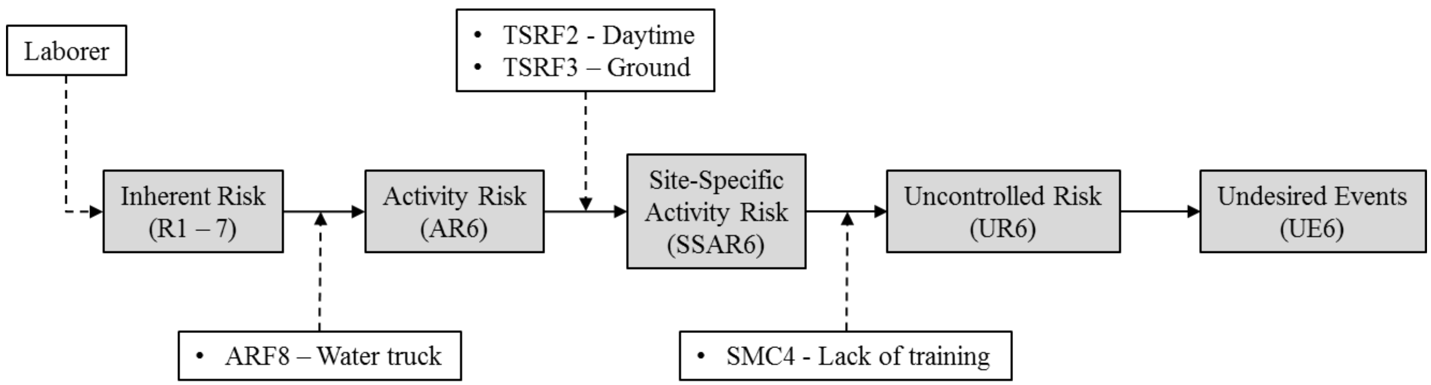


## A.6 NIOSH FACE REPORT 2001-10

Description

On April 16, 2001, a 17-year-old male part-time road construction laborer (the victim) died when he was run over by the rear wheels of a water truck. When the victim arrived at the work site, his employer asked him to ride with him in the cab of the water truck. After riding approximately 10 minutes, the employer asked him to get out and go to the rear of the truck to check the fluid gauge on the tank. The truck continued moving forward at 3 to 5 miles per hour. A coworker, who was driving a tamping roller behind the water truck, saw the victim get off the back of the moving truck after checking the fluid gauge and walk around the truck toward the cab on the passenger side. He then saw the victim stop just before the cab, where he stooped over, leaned under the truck and was run over. The employer last saw the victim in his driver's side mirror when the victim poked his head around the tank from his position on the ladder attached to the rear of the truck. He yelled to the victim to get down and move to the driver's side to get ready to close an external control under the truck on the driver's side. When the employer stopped the truck approximately 30 to 45 seconds after last seeing the victim, he looked back and saw the coworker waving and the victim lying on the road. The coworker called 911 from his cell phone.

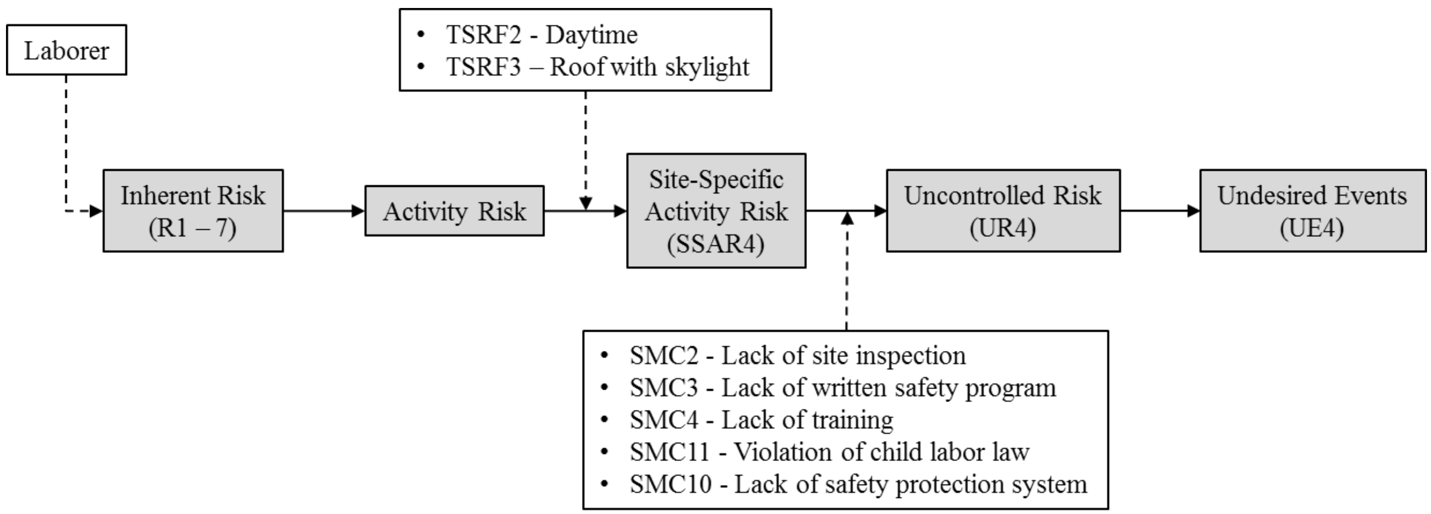
Model Application



Description

On January 17, 2001, a 15-year-old male laborer (the victim) died from injuries he sustained when he fell through a skylight to the lower ground level approximately 23 feet, 9 inches below. The company's president allowed the company's handyman to find someone to help him repair leaks in a flat roof over the company's three-sided warehouse. The handyman enlisted the help of his 15-year-old neighbor and brought him to the worksite. Neither the handyman nor laborer had received training in fall protection methods and no means of fall protection had been provided by the employer. They worked on the roof for approximately 6 hours, patching cracks with tar and gravel, and were nearly done with repairs, when the victim fell through an unguarded skylight. The handyman did not see the victim fall. Immediately following the incident, a worker inside the warehouse reported the incident to office personnel who immediately called 911. Personnel from the sheriff's office and emergency medical services (EMS) responded within 5 minutes.

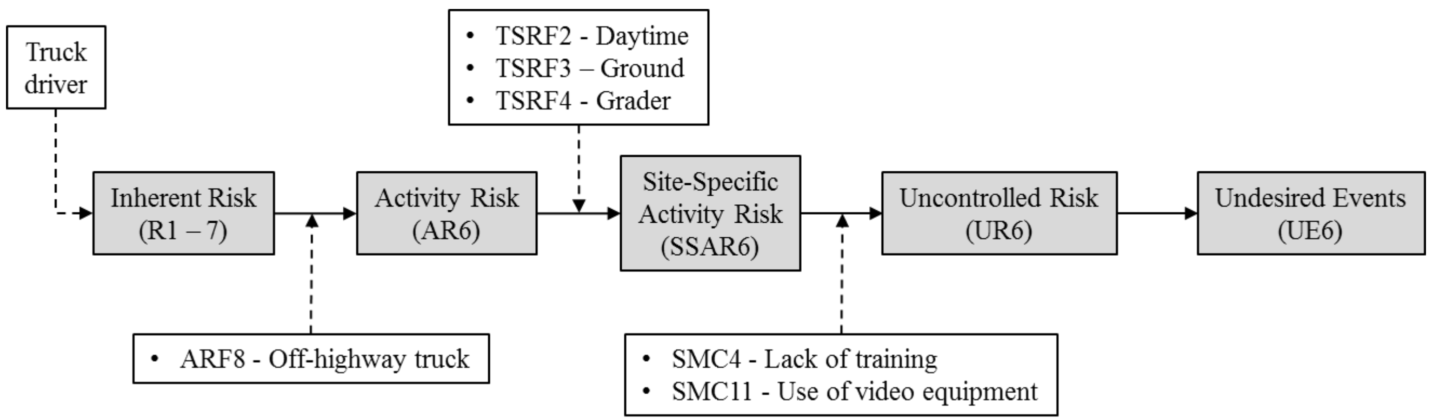
Model Application



## A.8 NIOSH FACE Report 2000-05

Description A 48-year-old male truck driver (the victim) died after the off-highway truck he was operating rolled 49 feet over an embankment and came to rest on its top in 4 feet of water. The victim was hauling dirt that was being cut from a bank to clear ground for a 3-mile stretch of a new freeway project. As the victim was traveling up a haulage road, a road grader that was scraping mud from the road was traveling toward him from the opposite direction. The victim steered the truck to the right to allow the grader to pass. As he did, a portion of the built-up haulage road gave way under the truck's right-side tires, causing the truck to overturn. The truck rolled over twice while traveling 49 feet down the embankment, and came to rest on its top in 4 feet of water. The grader operator immediately ran to the truck and pulled the victim clear. With the help of two flaggers, they placed the victim on the bottom of the truck cab. The two flaggers initiated cardiopulmonary resuscitation (CPR) on the victim while the emergency medical service (EMS) was called from a company truck. The EMS arrived at the scene within 8 minutes and summoned the county coroner, who pronounced the victim dead at the scene.

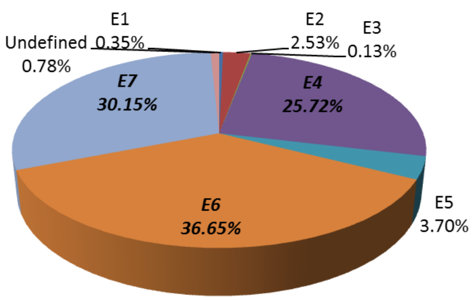
Model Application



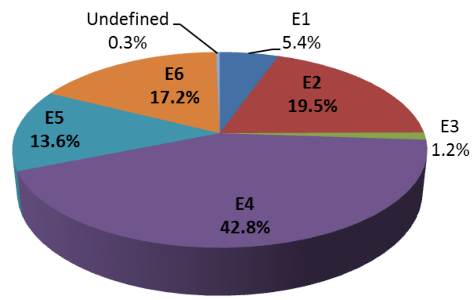
# Appendix B – 1st Level Risk Types by Occupations

| Days Away Injury | Fatality |
|---|---|

**47-2000 Construction Trades Workers**

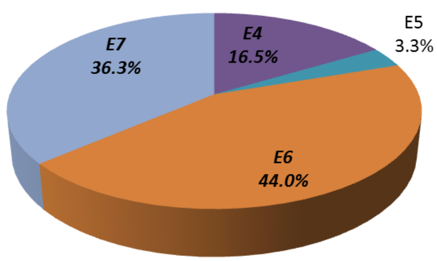



N: 62,760

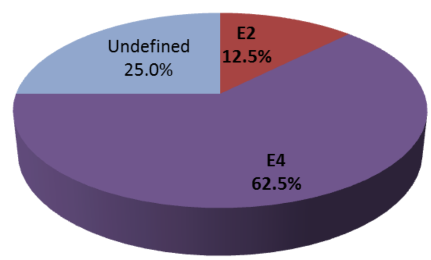



N: 575

**47-2020 Brickmasons, Blockmasons, and Stonemasons**

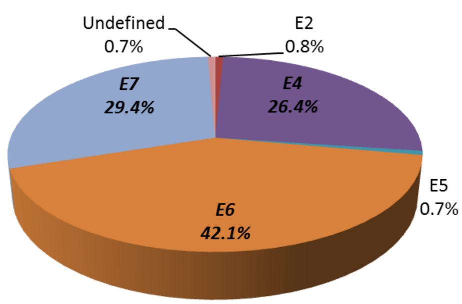



N: 910

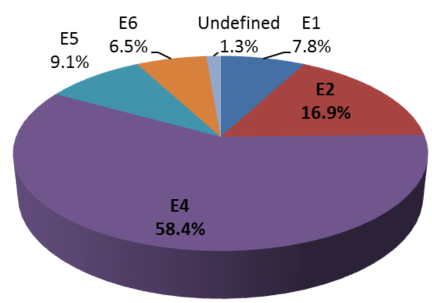



N: 8

**47-2030 Carpenters**



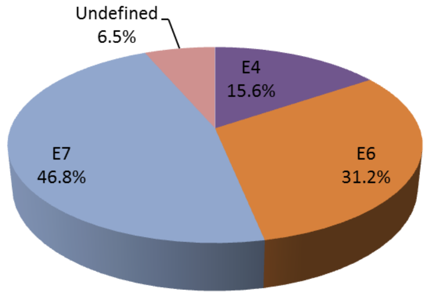

N: 10,630




N: 77

| Days Away Injury | Fatality |
| --- | --- |

**47-2040 Carpet, Floor, and Tile Installers and Finishers**

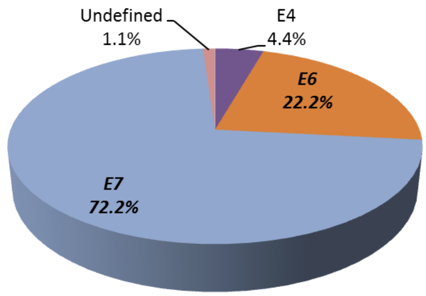



N: 770

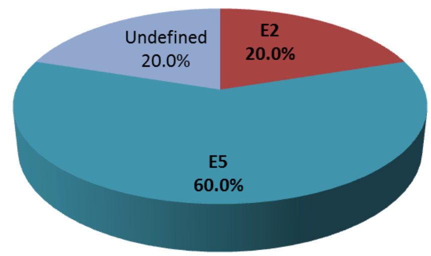
**N/A**

N: 0

**47-2050 Cement Masons, Concrete Finishers, and Terrazzo Workers**

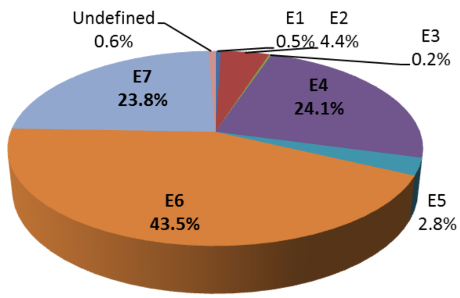



N: 900

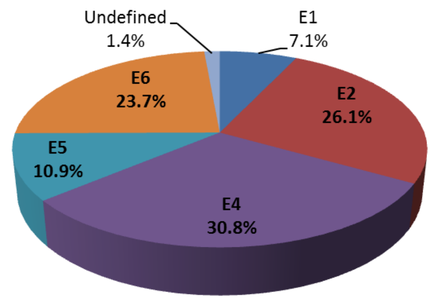



N: 5

**47-2060 Construction Laborers**

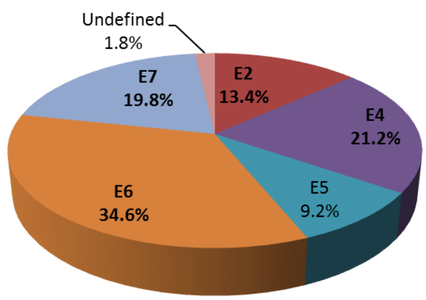



N: 19,330

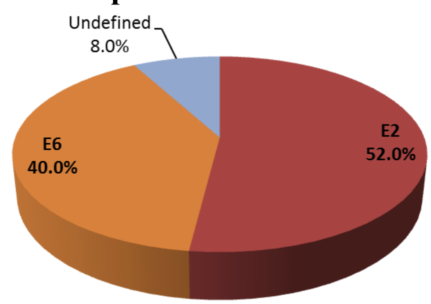



N: 211

**47-2070 Construction Equipment Operators**



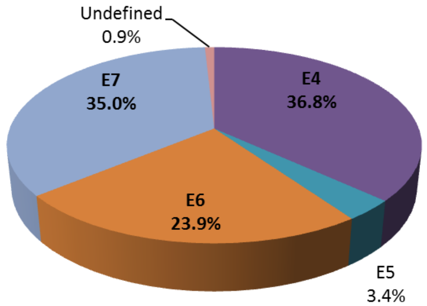

N: 2,170



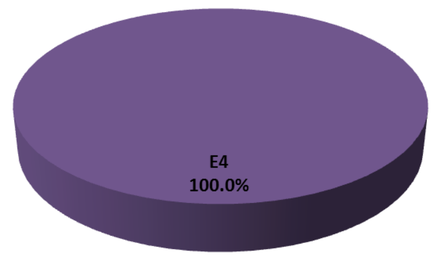

N: 25

| Days Away Injury | Fatality |
|---|---|

**47-2080 Drywall Installers, Ceiling Tile Installers, and Tapers**

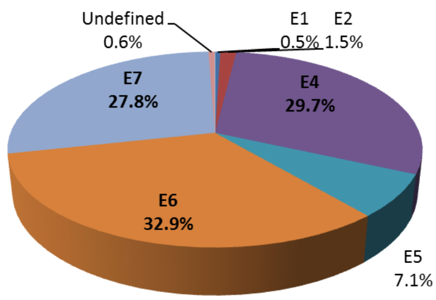



N: 1,170

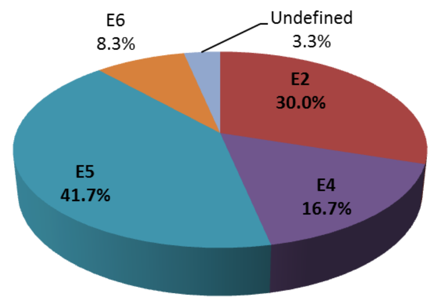



N: 11

**47-2110 Electricians**

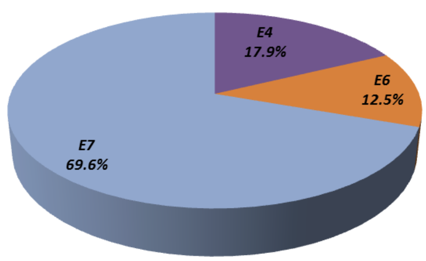



N: 8,210




N: 60

**47-2120 Glaziers**

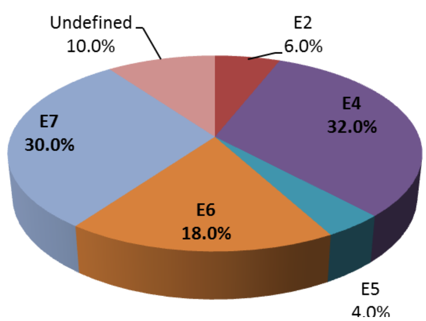



N: 560

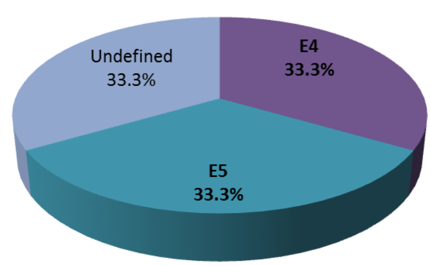
**N/A**

N: 0

**47-2130 Insulation Workers**



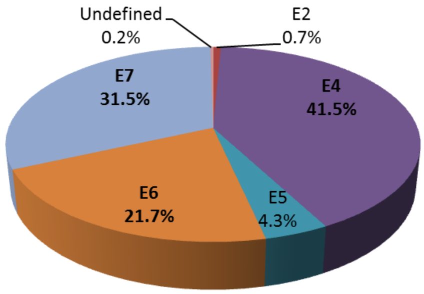

N: 500



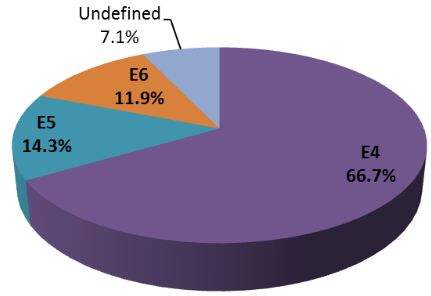

N: 3

| Days Away Injury | Fatality |
|---|---|

**47-2140 Painters and Paperhangers**

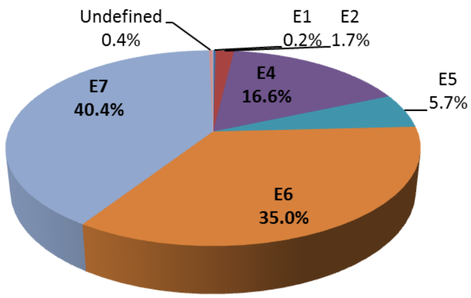



N: 4,190

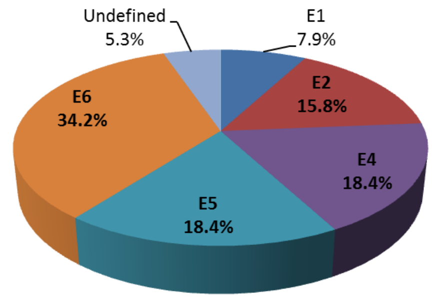



N: 42

**47-2150 Pipelayers, Plumbers, Pipefitters, and Steamfitters**

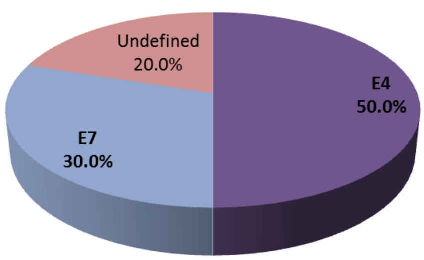



N: 8,310




N: 38

**47-2160 Plasterers and Stucco Masons**

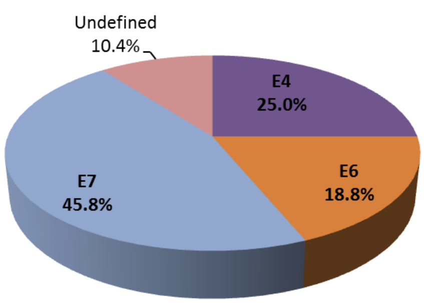



N: 100

**N/A**

N: 0

**47-2170 Reinforcing Iron and Rebar Workers**



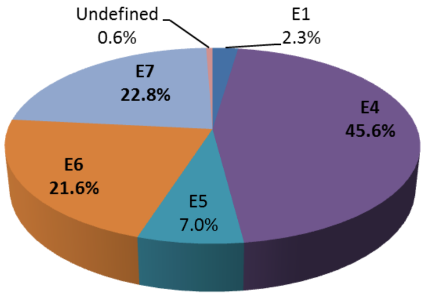

N: 480

**N/A**

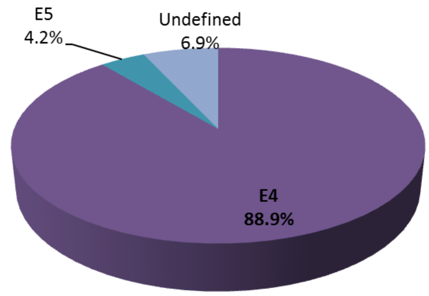
N: 0

| Days Away Injury | Fatality |
|---|---|

**47-2180 Roofers**

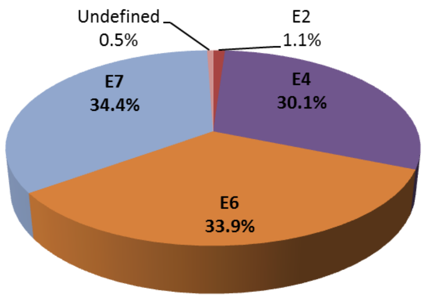



N: 1,710

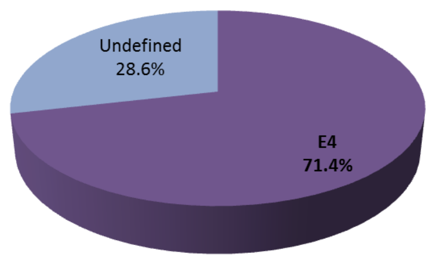



N: 72

**47-2210 Sheet Metal Workers**

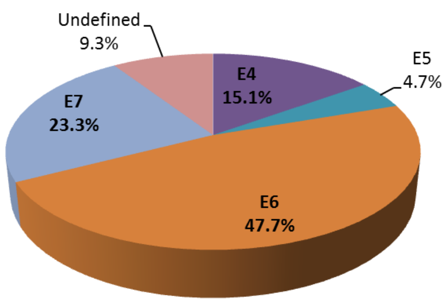



N: 1,830

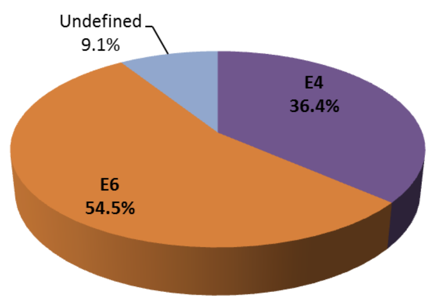



N: 7

**47-2220 Structural Iron and Steel Workers**



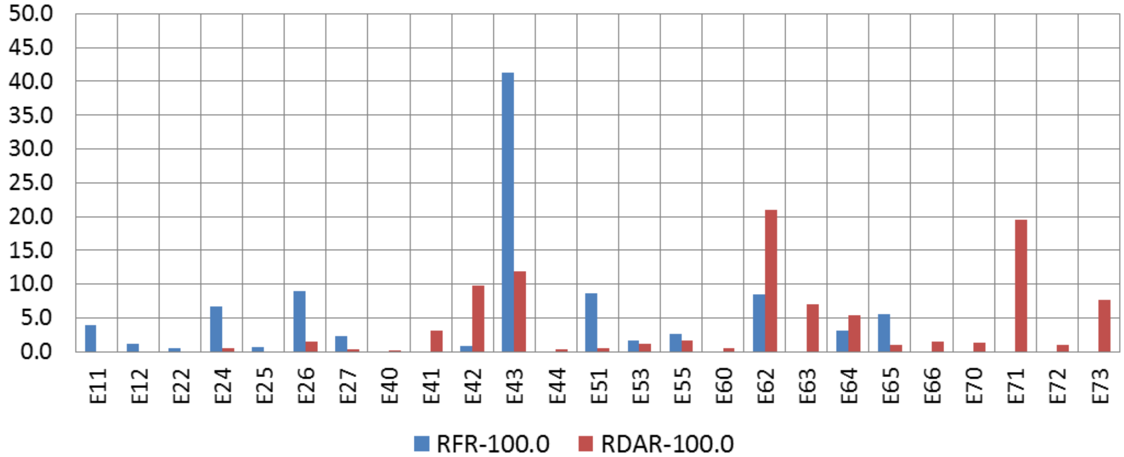

N: 860



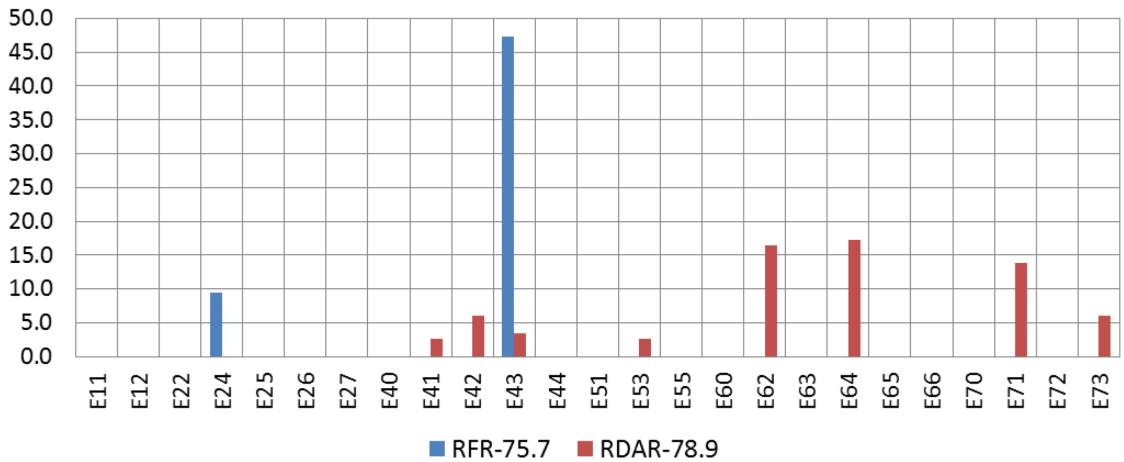

N: 11

# Appendix C – 2nd Level Risk Types by Occupations

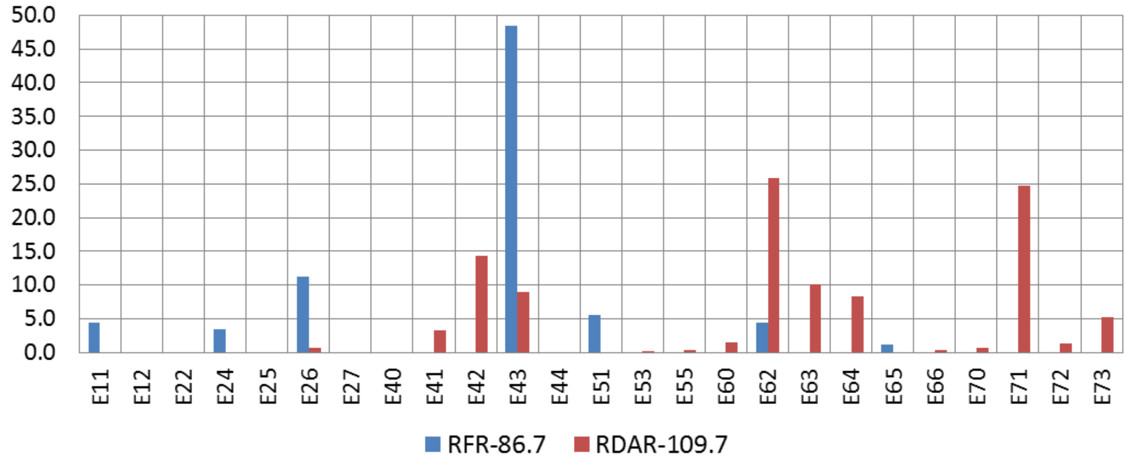
**47-2000 Construction Trades Workers**



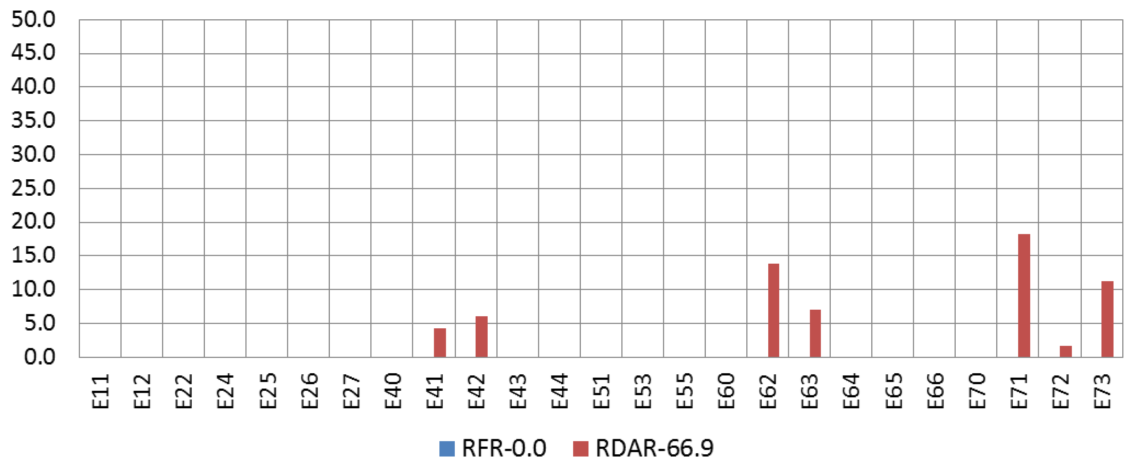

**47-2020 Brickmasons, Blockmasons, and Stonemasons**



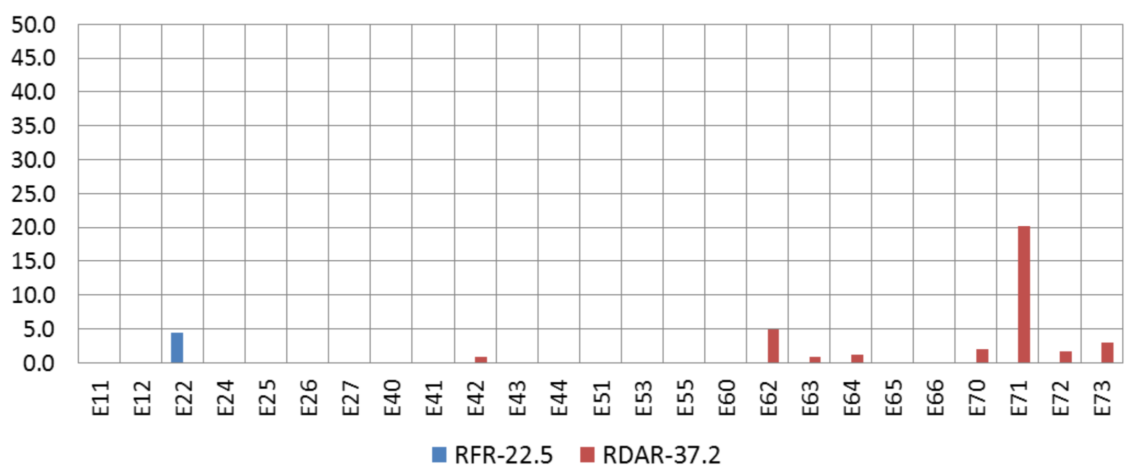
**47-2030 Carpenters**



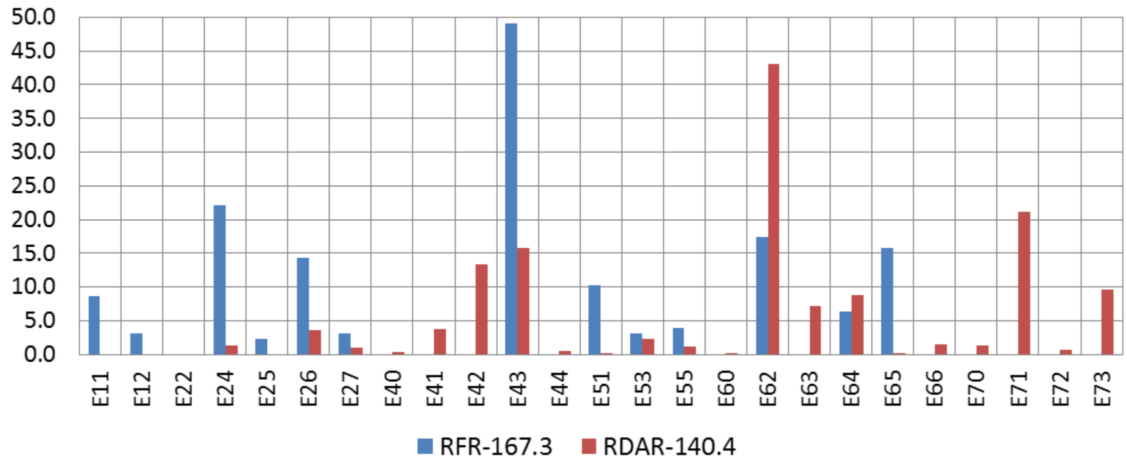

**47-2040 Carpet, Floor, and Tile Installers and Finishers**



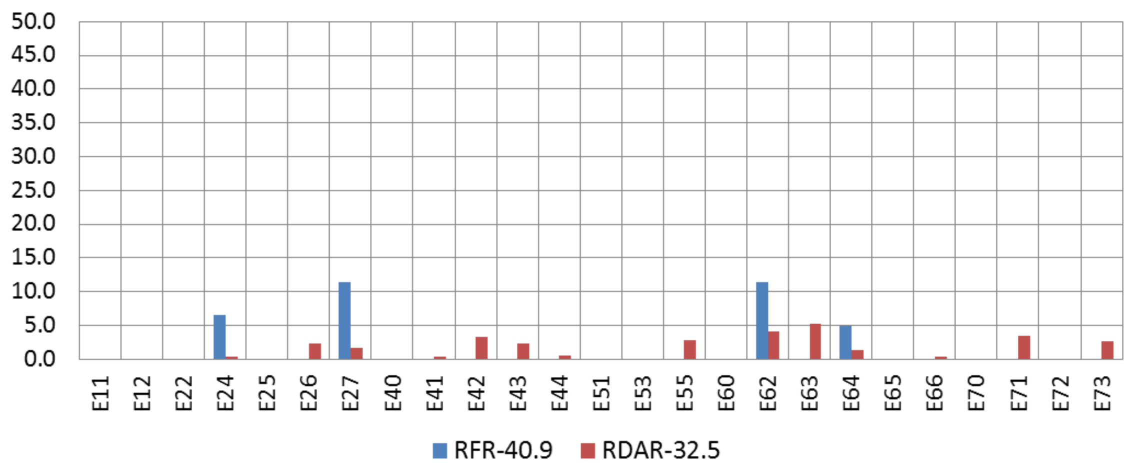

**47-2050 Cement Masons, Concrete Finishers, and Terrazzo Workers**



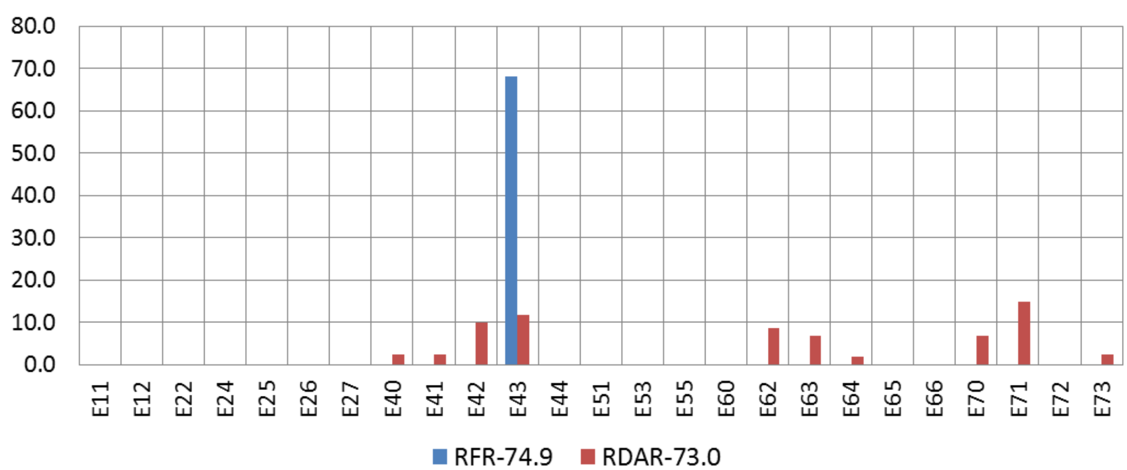
**47-2060 Construction Laborers**



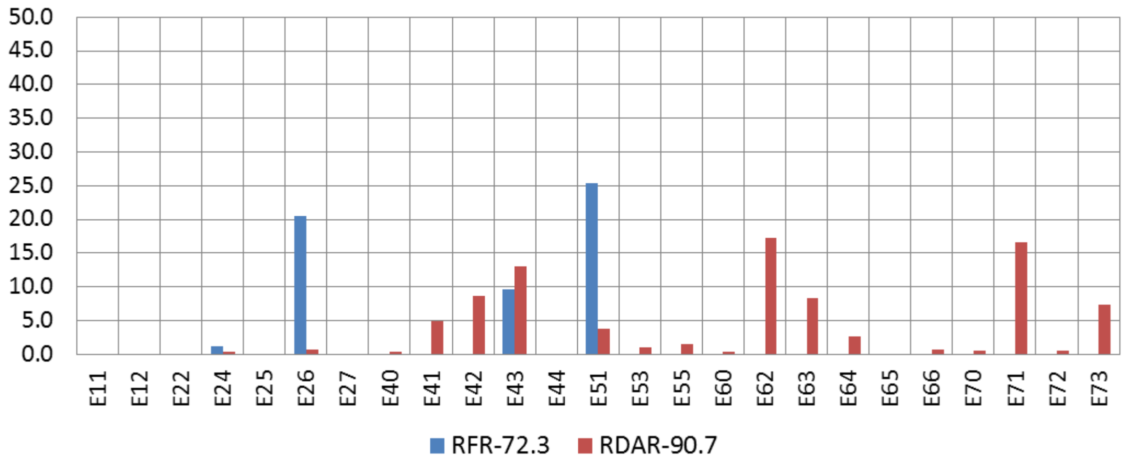

**47-2070 Construction Equipment Operators**



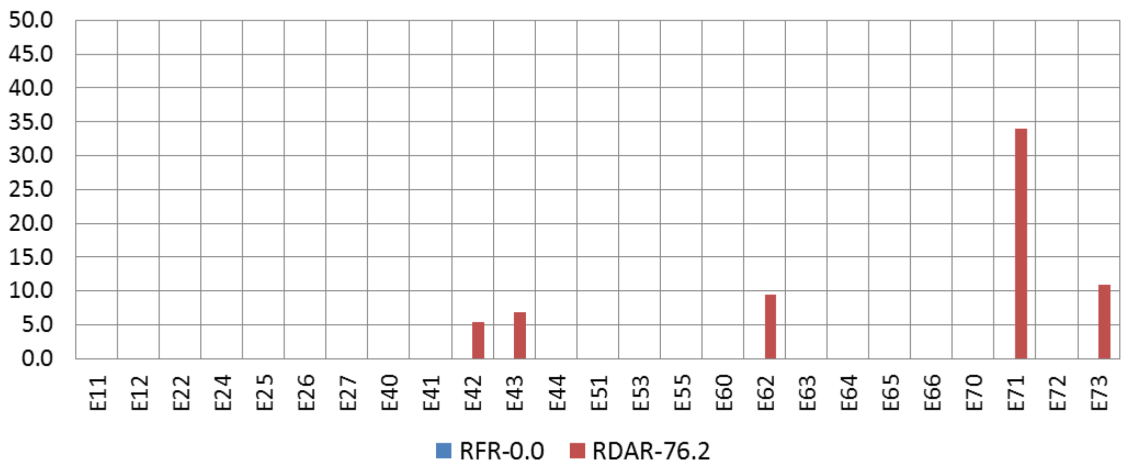

**47-2080 Drywall Installers, Ceiling Tile Installers, and Tapers**



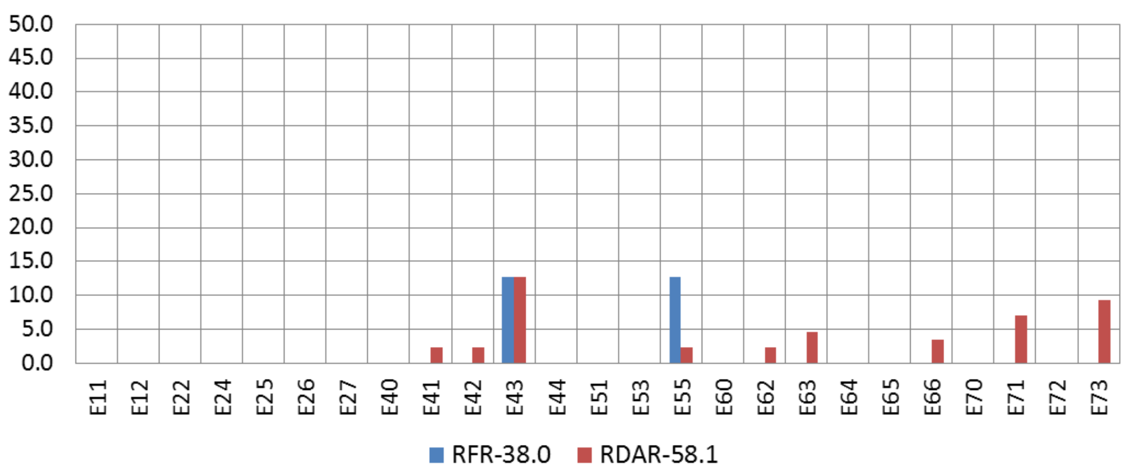
## 47-2110 Electricians



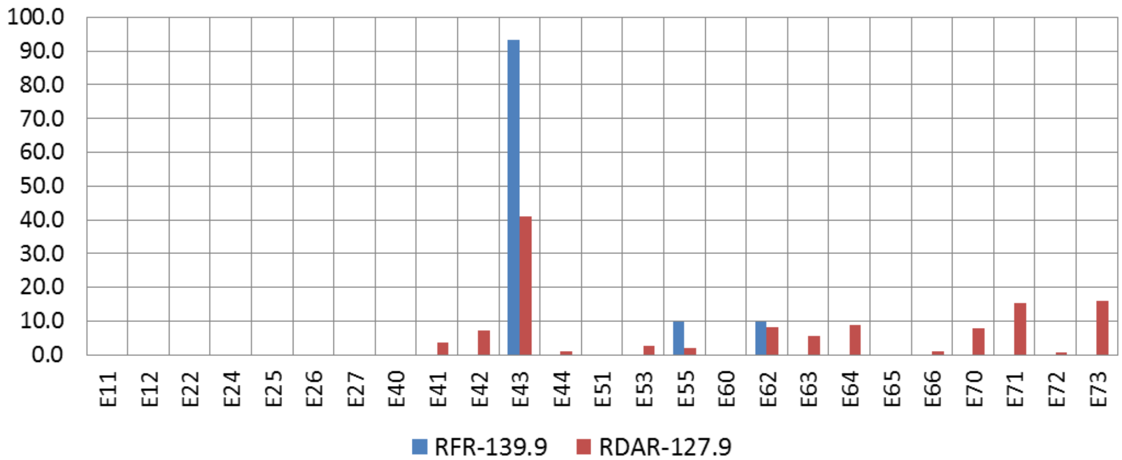

## 47-2120 Glaziers



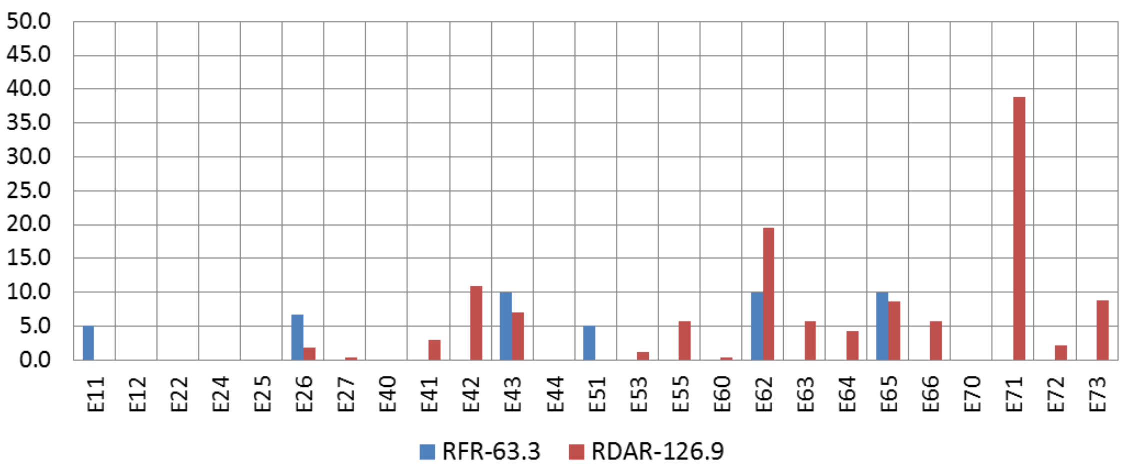

## 47-2130 Insulation Workers



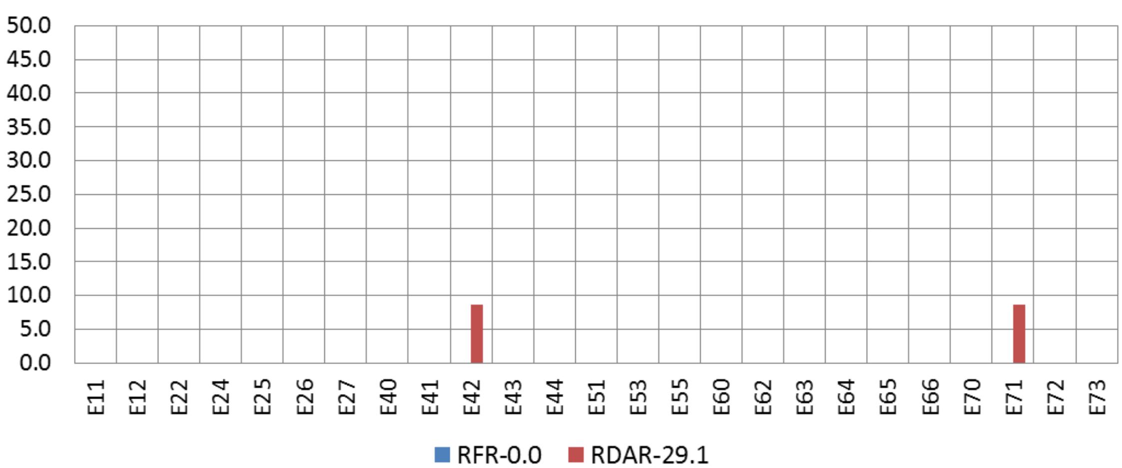
**47-2140 Painters and Paperhangers**



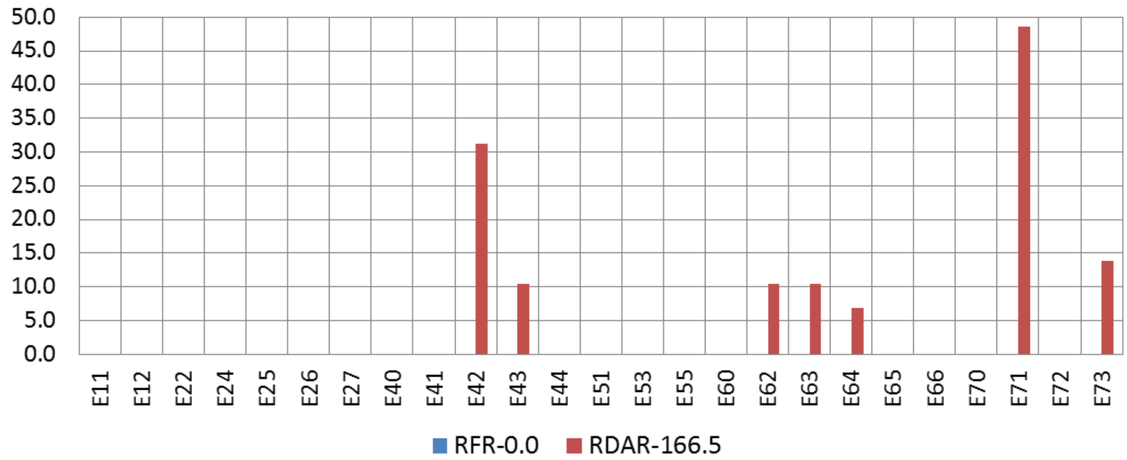

**47-2150 Pipelayers, Plumbers, Pipefitters, and Steamfitters**



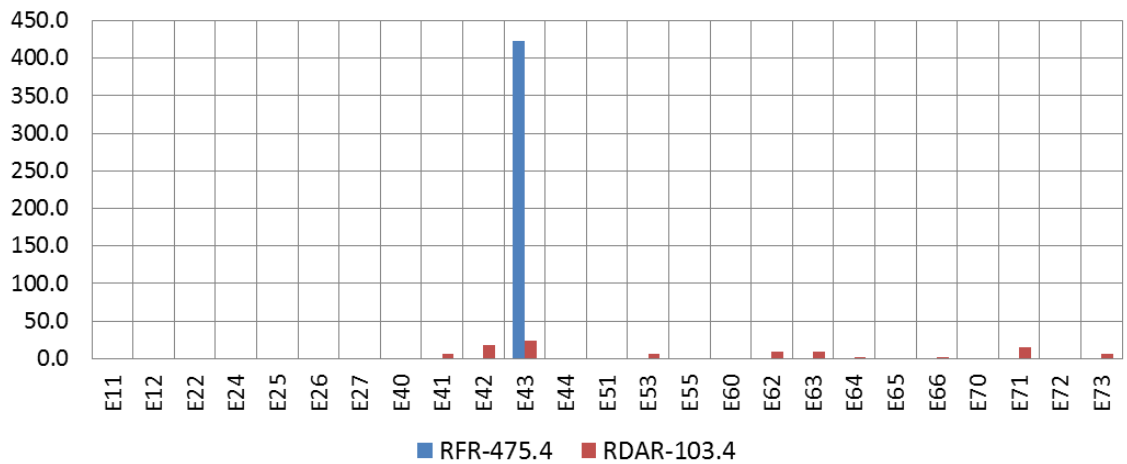

**47-2160 Plasterers and Stucco Masons**



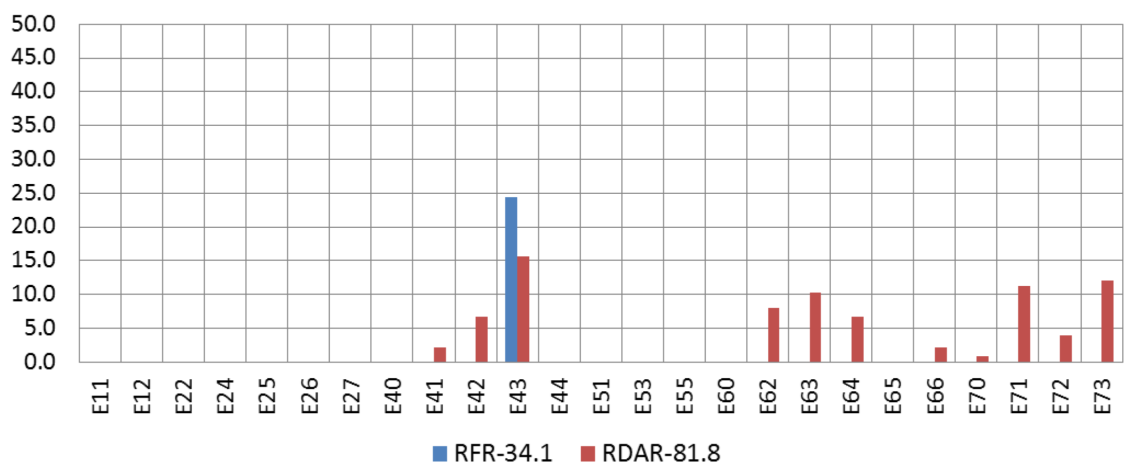
## 47-2170 Reinforcing Iron and Rebar Workers



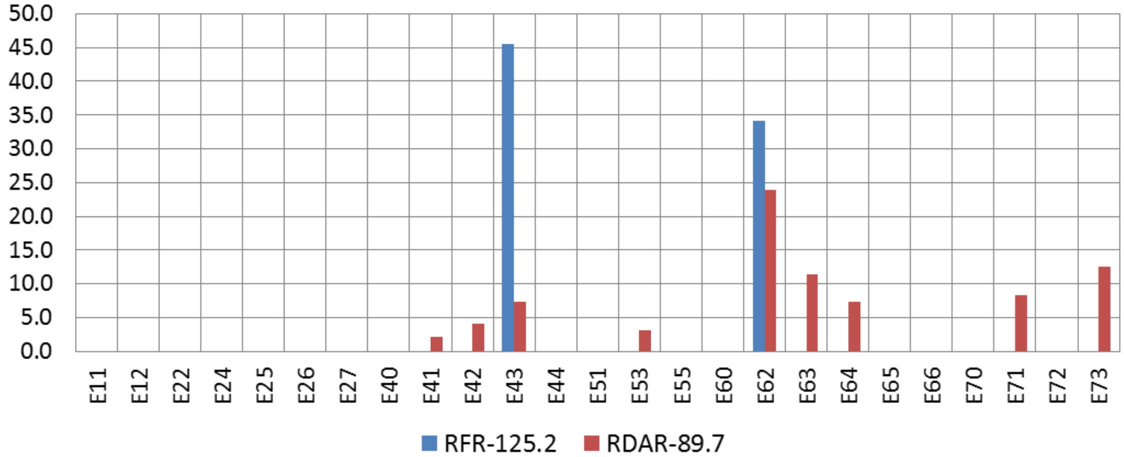

## 47-2180 Roofers




## 47-2210 Sheet Metal Workers



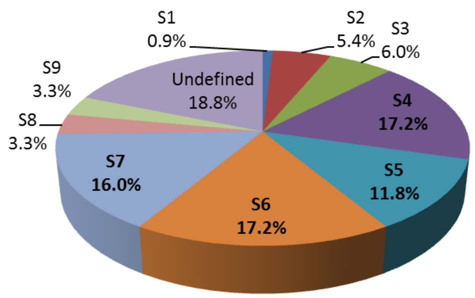
**47-2220 Structural Iron and Steel Workers**



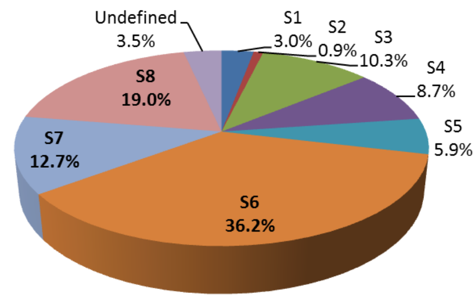
# Appendix D – 1st Level Sources of Injury by Occupations

| Days Away Injury | Fatality |
|---|---|

### 47-2000 Construction Trades Workers

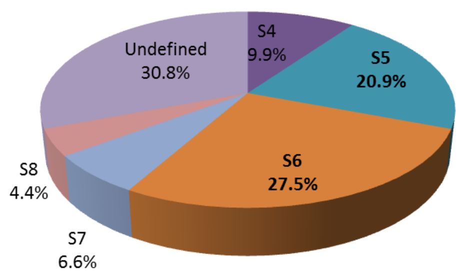



N: 62,760

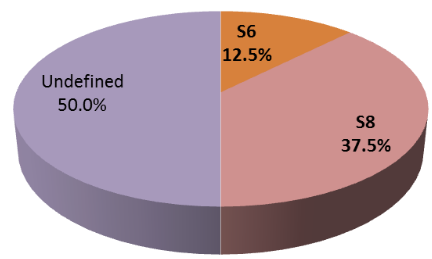



N: 575

### 47-2020 Brickmasons, Blockmasons, and Stonemasons

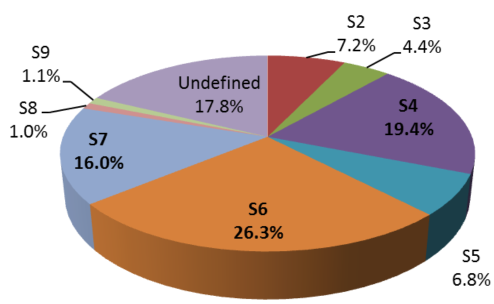



N: 910

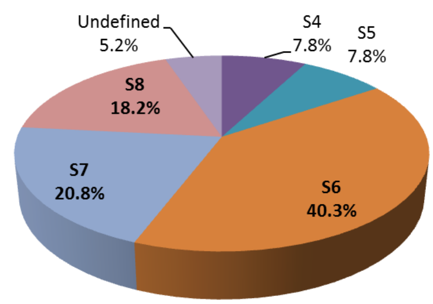



N: 8

### 47-2030 Carpenters



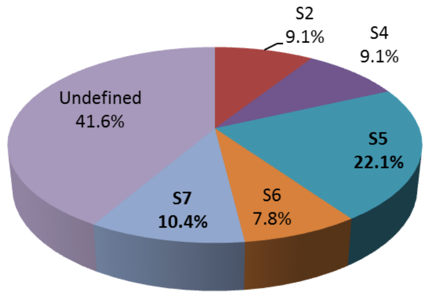

N: 10,630




N: 77

| Days Away Injury | Fatality |
|---|---|

**47-2040 Carpet, Floor, and Tile Installers and Finishers**

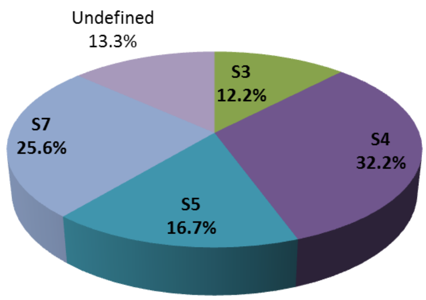



N: 770

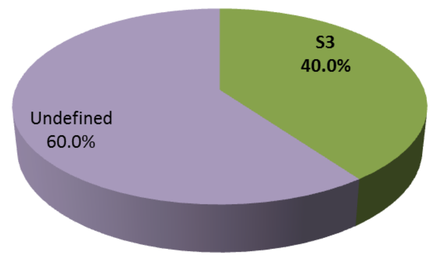
**N/A**

N: 0

**47-2050 Cement Masons, Concrete Finishers, and Terrazzo Workers**

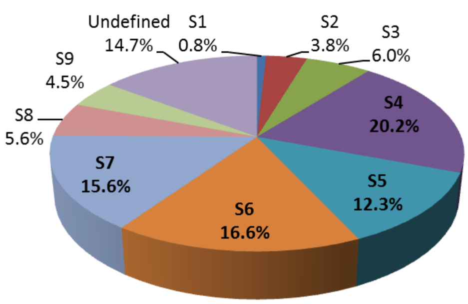



N: 900

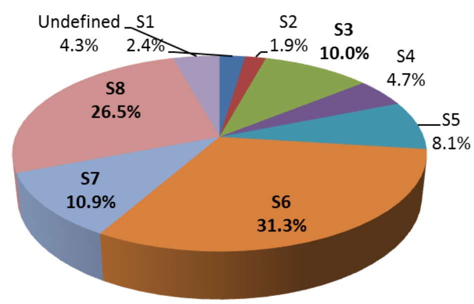



N: 5

**47-2060 Construction Laborers**

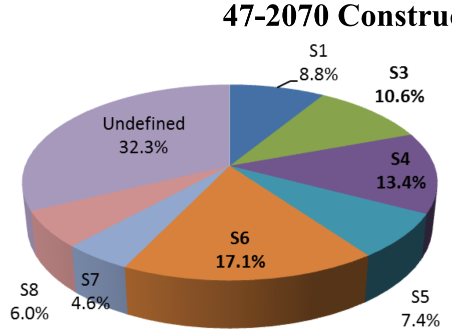



N: 19,330

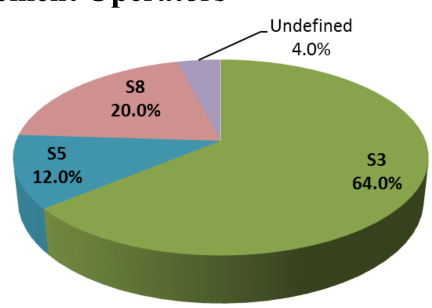



N: 211

**47-2070 Construction Equipment Operators**



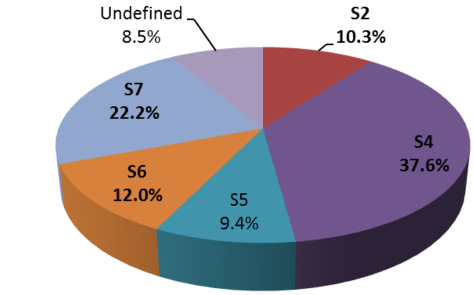

N: 2,170



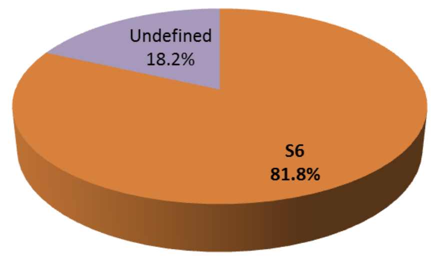

N: 25

| Days Away Injury | Fatality |
|---|---|

**47-2080 Drywall Installers, Ceiling Tile Installers, and Tapers**

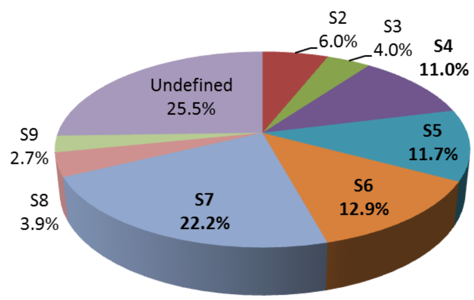



N: 1,170

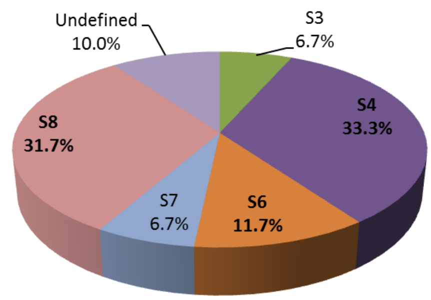



N: 11

**47-2110 Electricians**

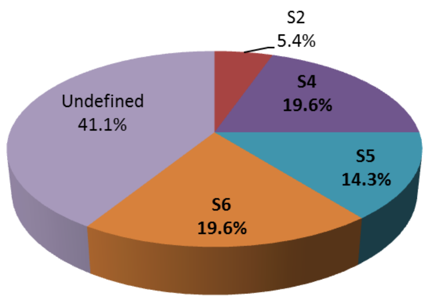



N: 8,210




N: 60

**47-2120 Glaziers**

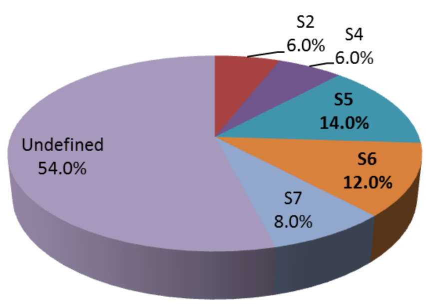



N: 560

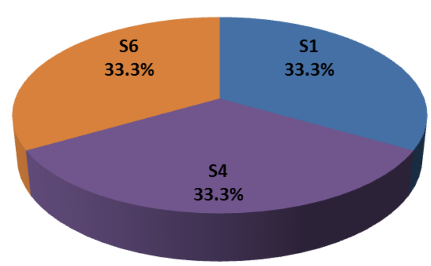
**N/A**

N: 0

**47-2130 Insulation Workers**



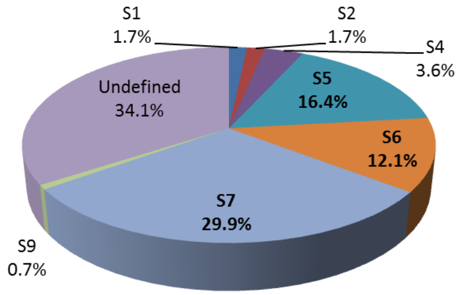

N: 500



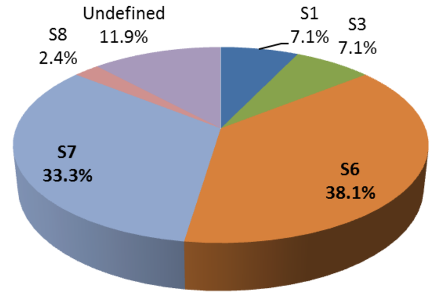

N: 3

| Days Away Injury | Fatality |
| --- | --- |

## 47-2140 Painters and Paperhangers

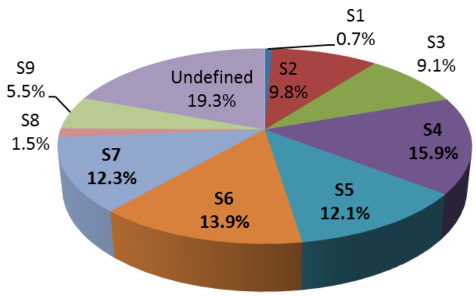



N: 4,190

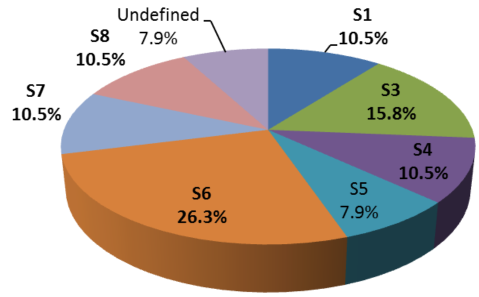



N: 42

## 47-2150 Pipelayers, Plumbers, Pipefitters, and Steamfitters

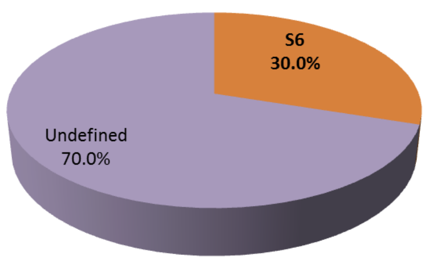



N: 8,310




N: 38

## 47-2160 Plasterers and Stucco Masons

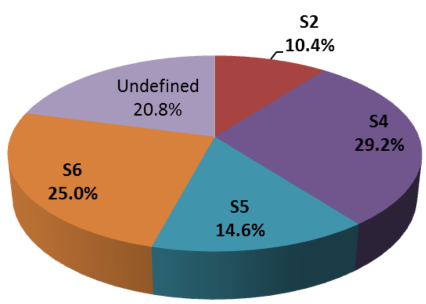



N: 100

**N/A**

N: 0

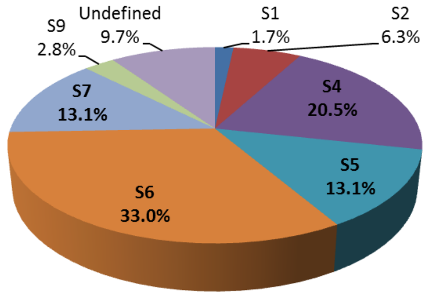
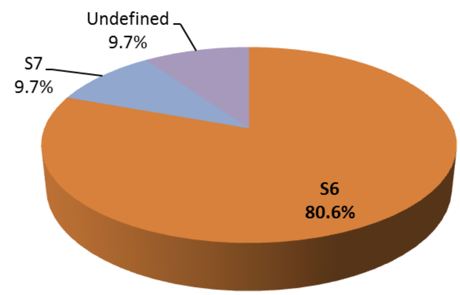
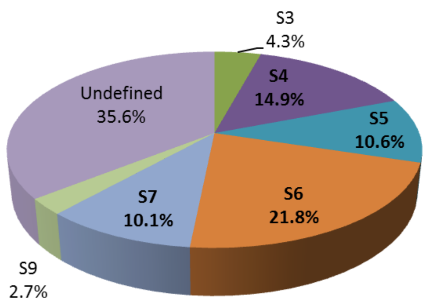
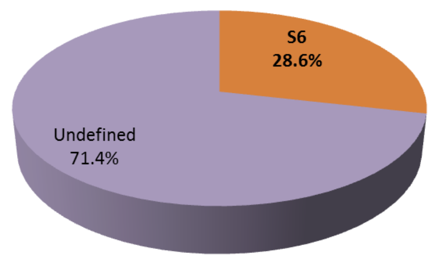
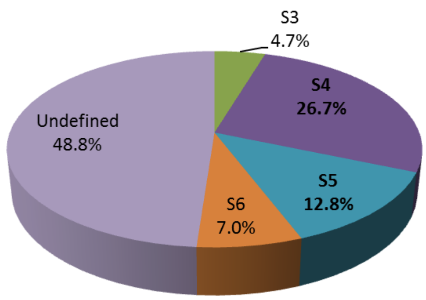
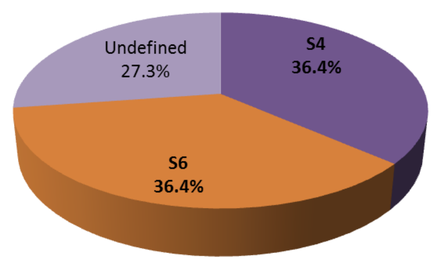
## 47-2170 Reinforcing Iron and Rebar Workers




N: 480

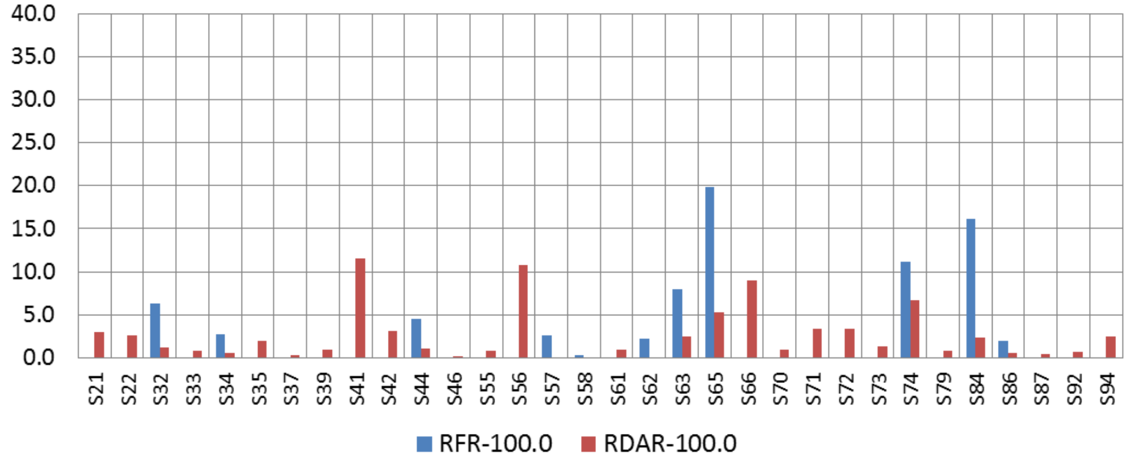
**N/A**

N: 0

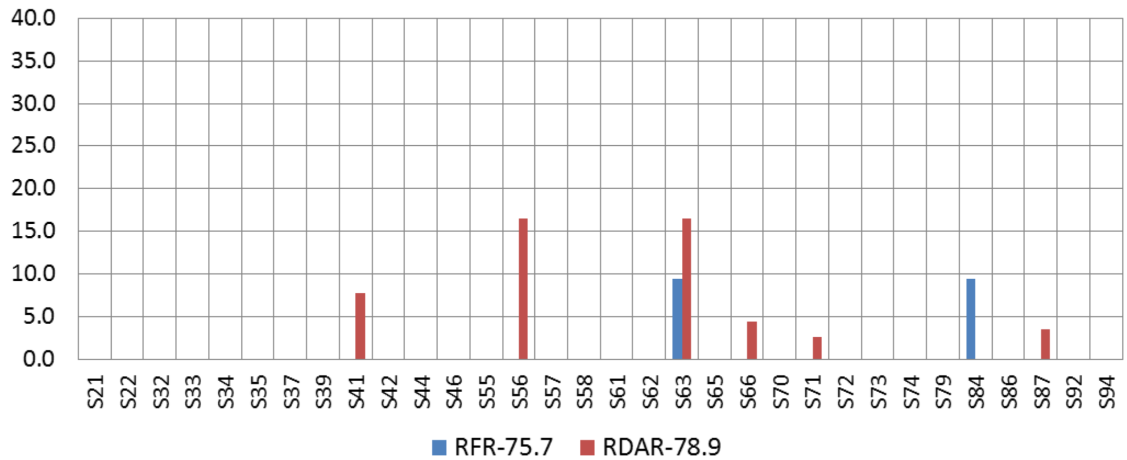
| Days Away Injury | Fatality |
|---|---|
| **47-2180 Roofers** | |
|  |  |
| N: 1,710 | N: 72 |
| **47-2210 Sheet Metal Workers** | |
|  |  |
| N: 1,830 | N: 7 |
| **47-2220 Structural Iron and Steel Workers** | |
|  |  |
| N: 860 | N: 11 |

## Appendix E – 2nd Level Sources of Injury by Occupations

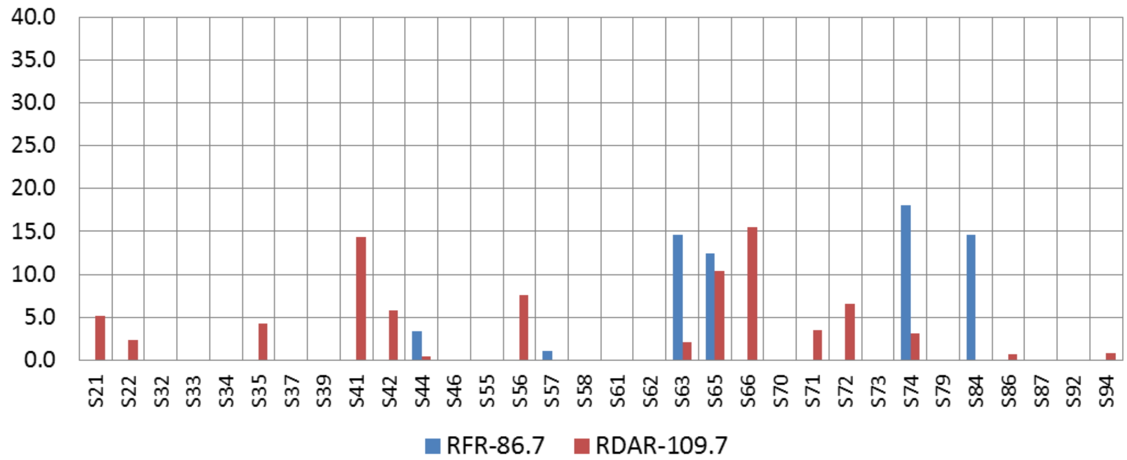
**47-2000 Construction Trades Workers**



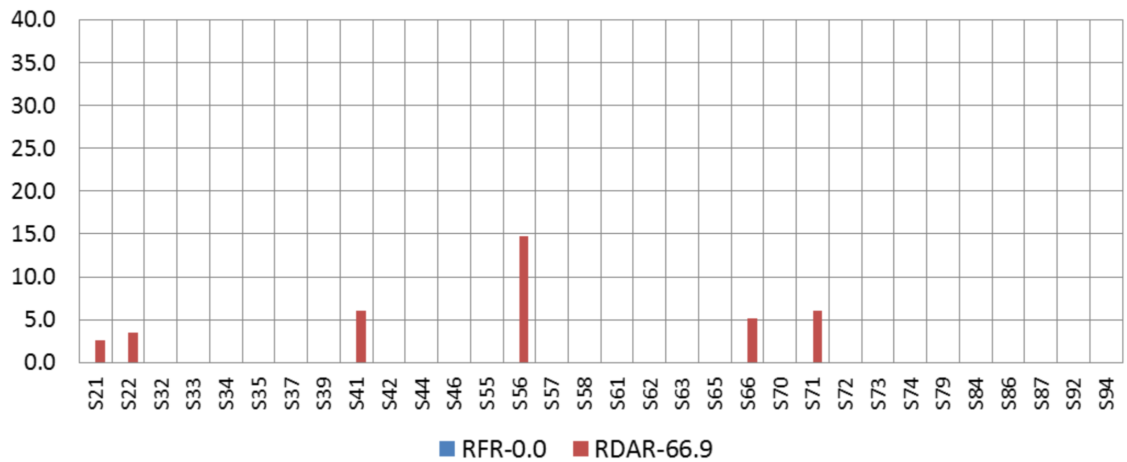

**47-2020 Brickmasons, Blockmasons, and Stonemasons**



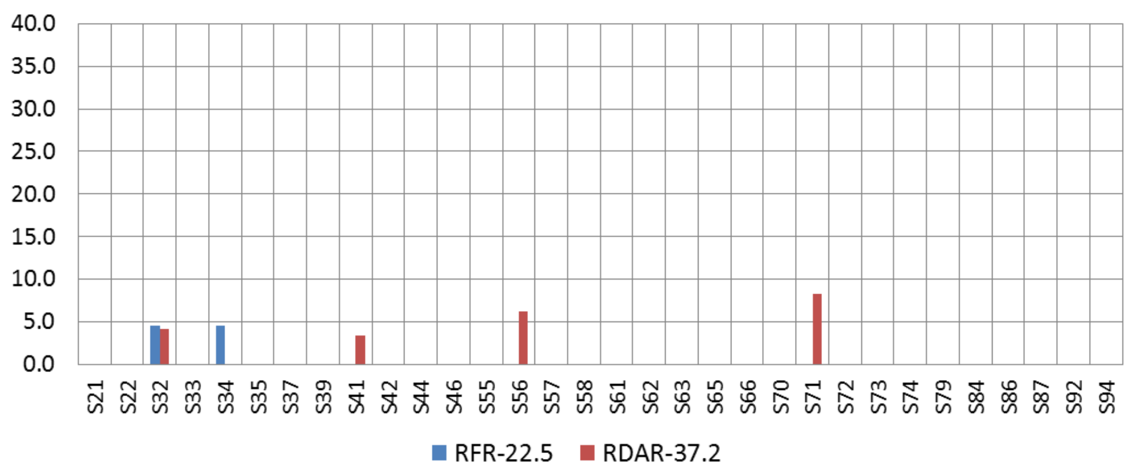
**47-2030 Carpenters**



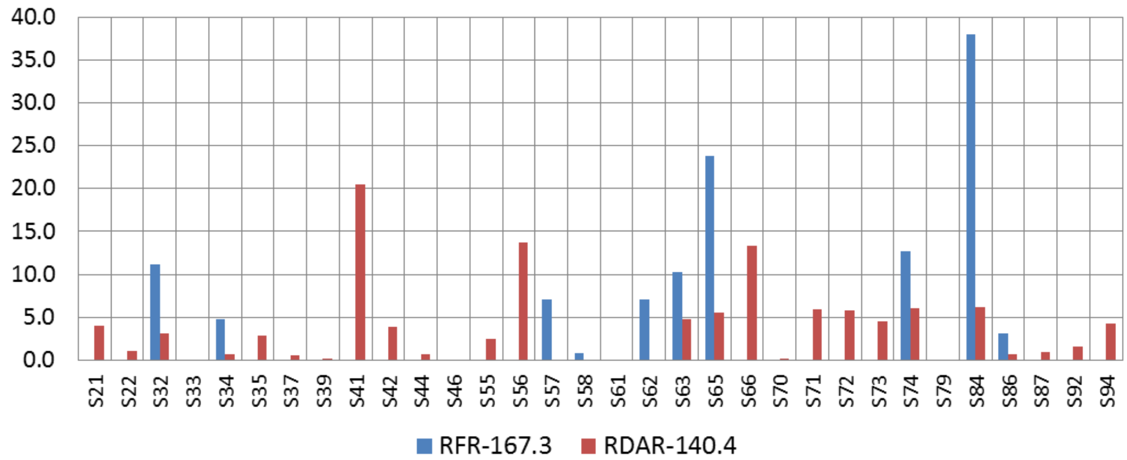

**47-2040 Carpet, Floor, and Tile Installers and Finishers**



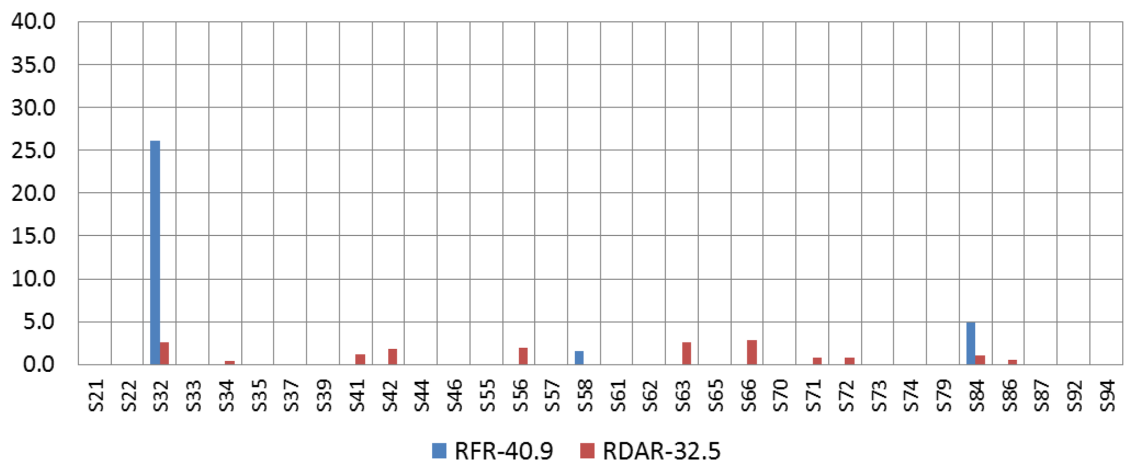

**47-2050 Cement Masons, Concrete Finishers, and Terrazzo Workers**



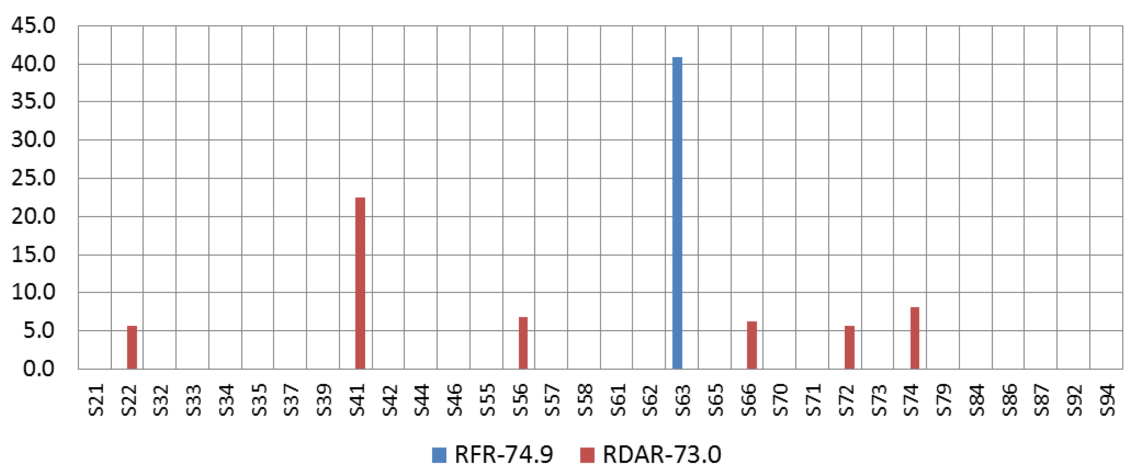
**47-2060 Construction Laborers**



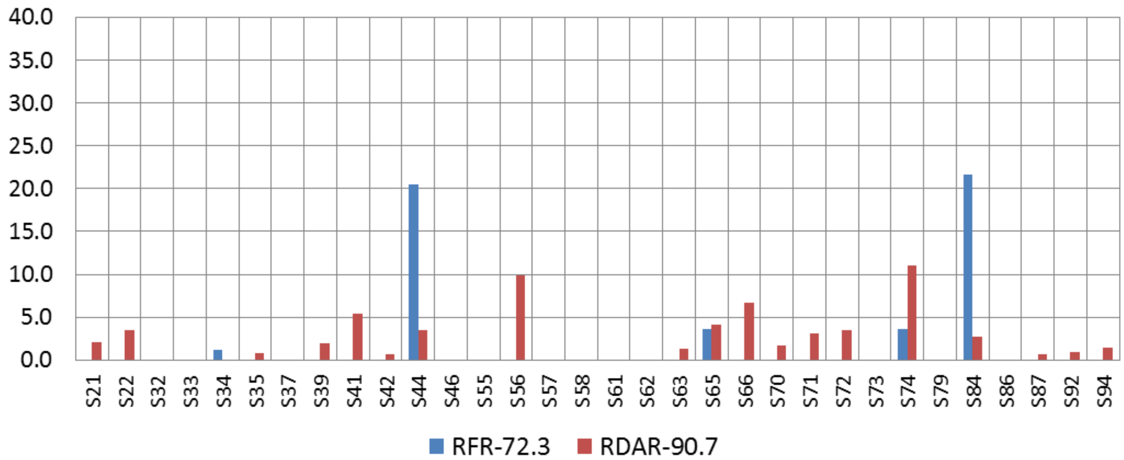

**47-2070 Construction Equipment Operators**



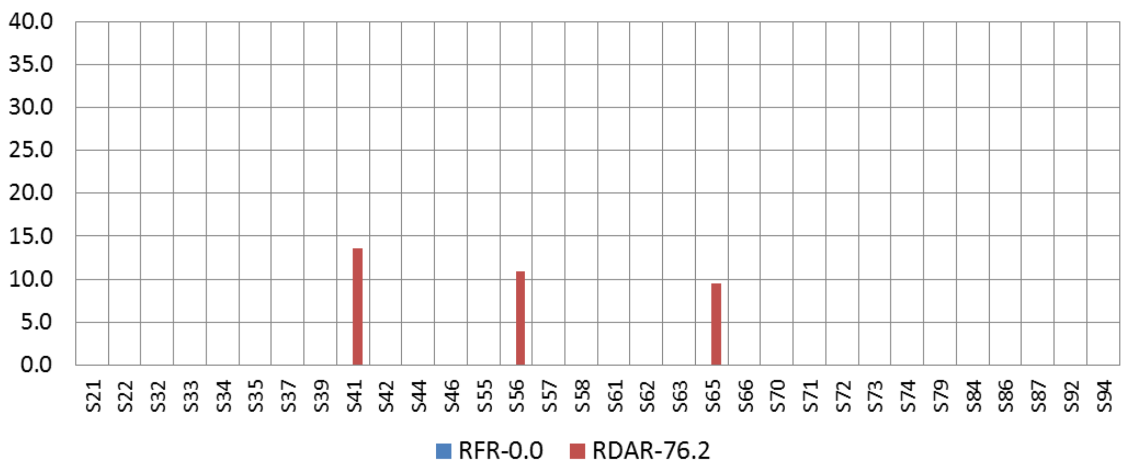

**47-2080 Drywall Installers, Ceiling Tile Installers, and Tapers**



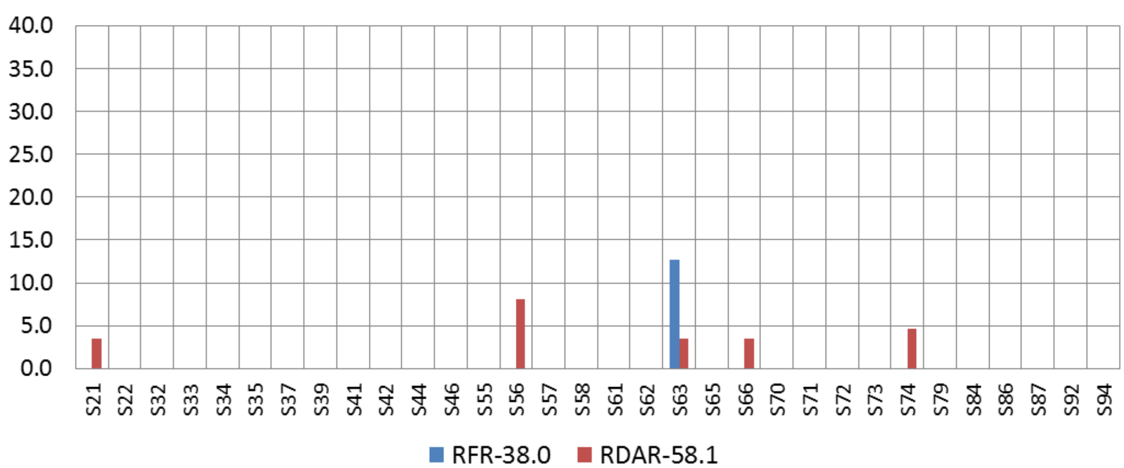
## 47-2110 Electricians



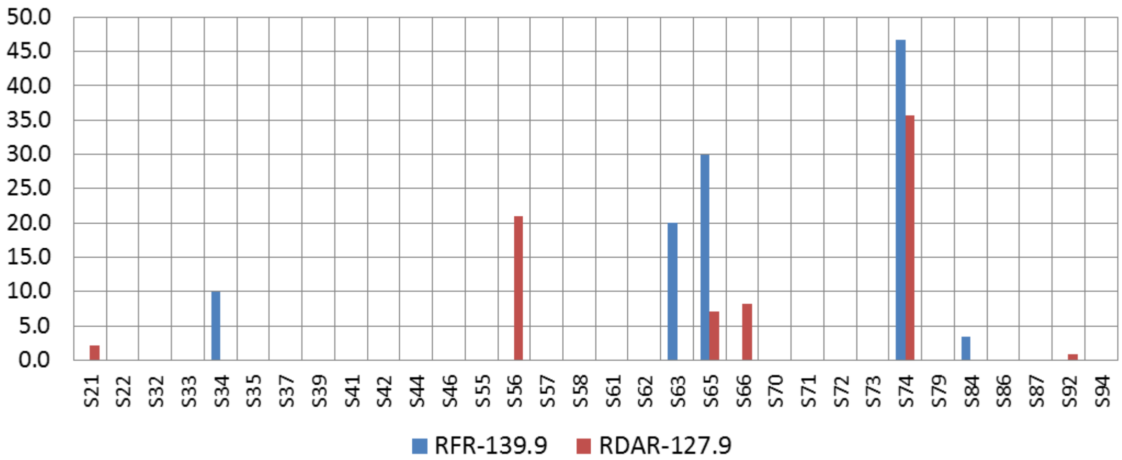

## 47-2120 Glaziers



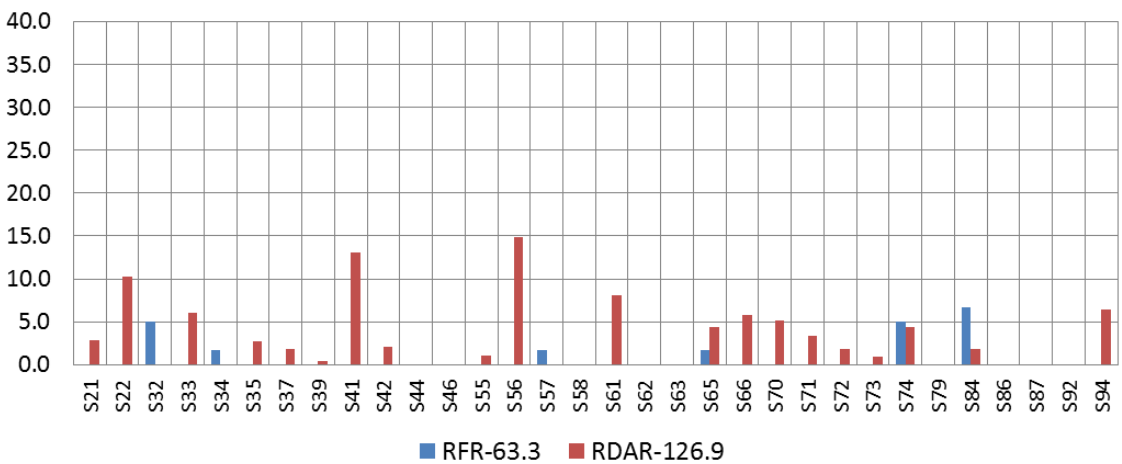

## 47-2130 Insulation Workers



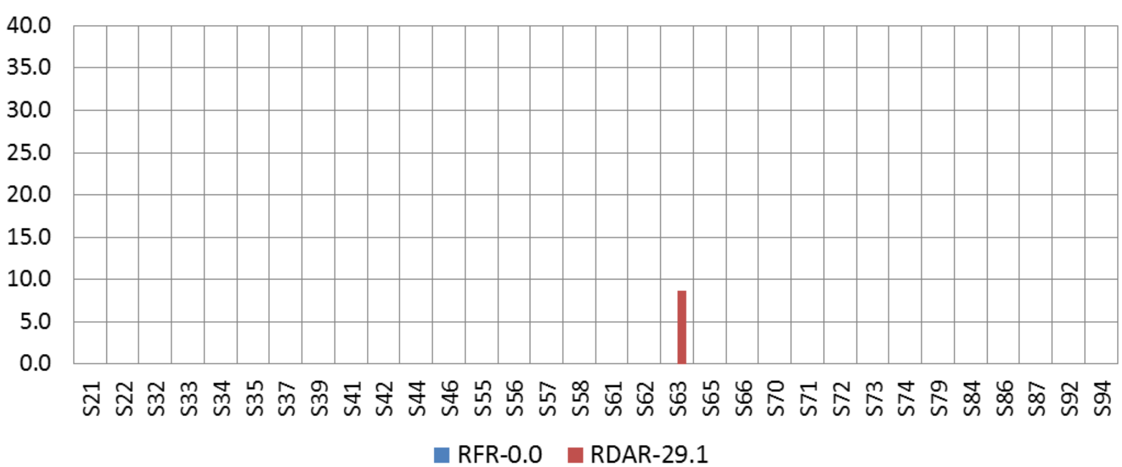
## 47-2140 Painters and Paperhangers



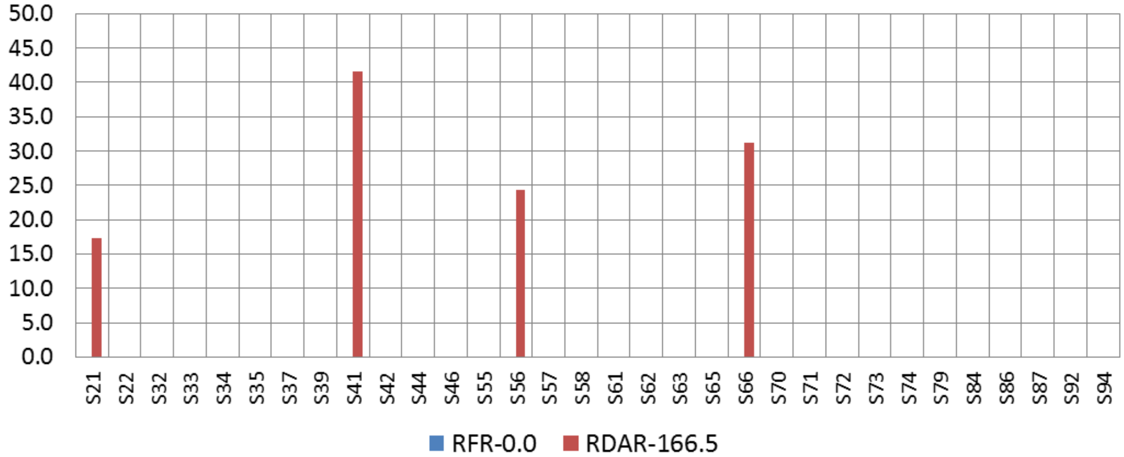

## 47-2150 Pipelayers, Plumbers, Pipefitters, and Steamfitters



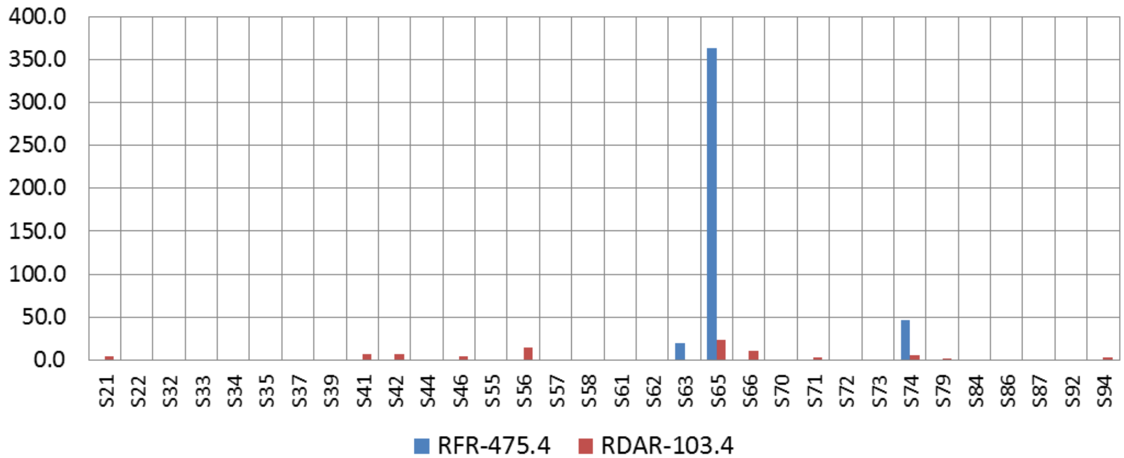

## 47-2160 Plasterers and Stucco Masons



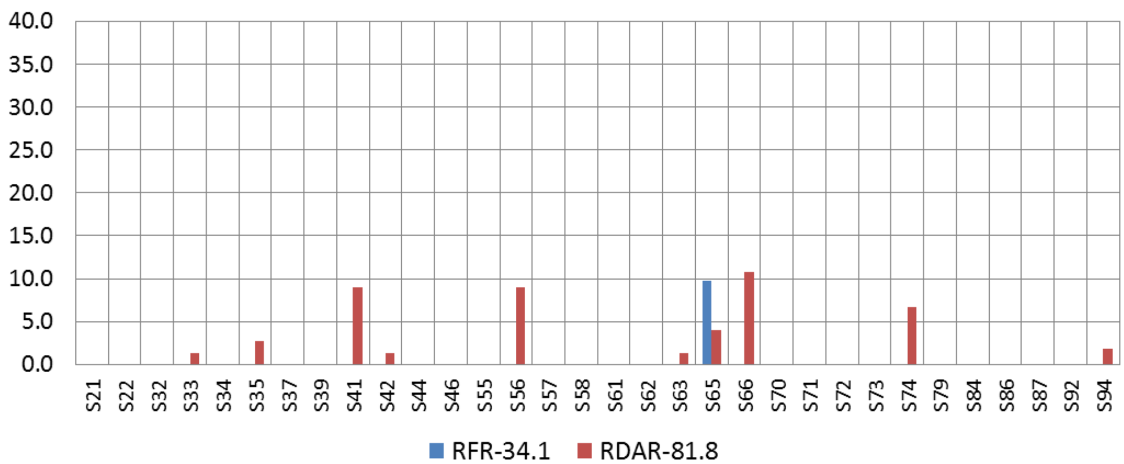
## 47-2170 Reinforcing Iron and Rebar Workers



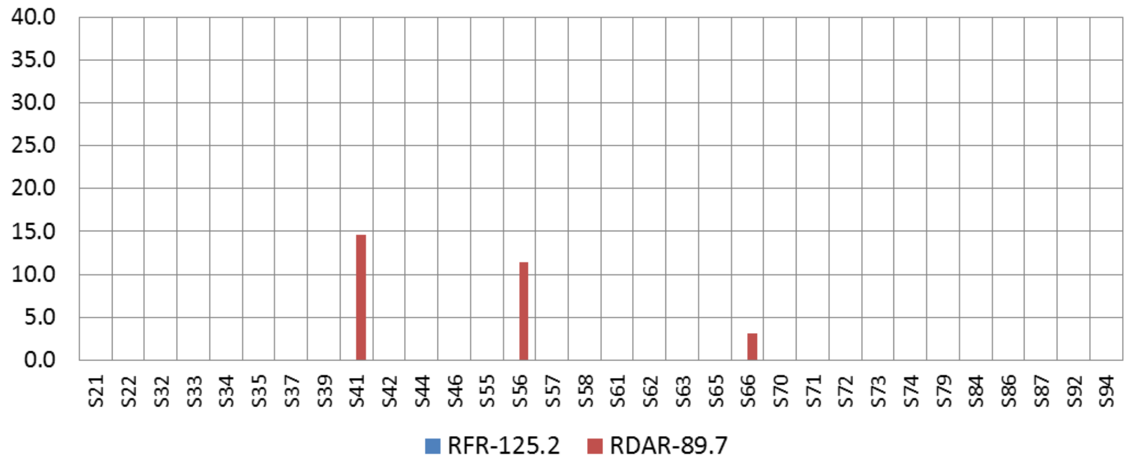

## 47-2180 Roofers




## 47-2210 Sheet Metal Workers

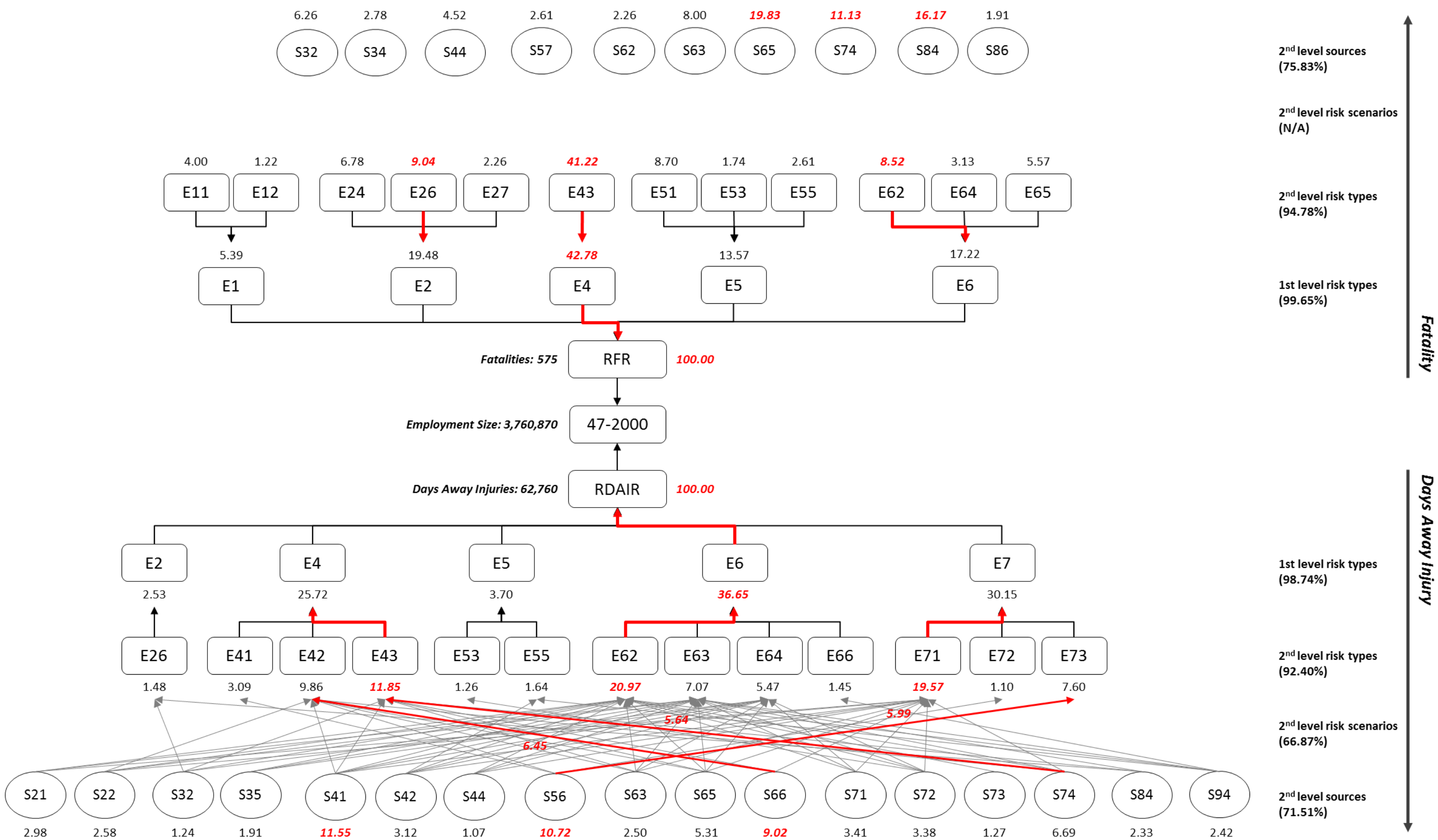


## 47-2220 Structural Iron and Steel Workers

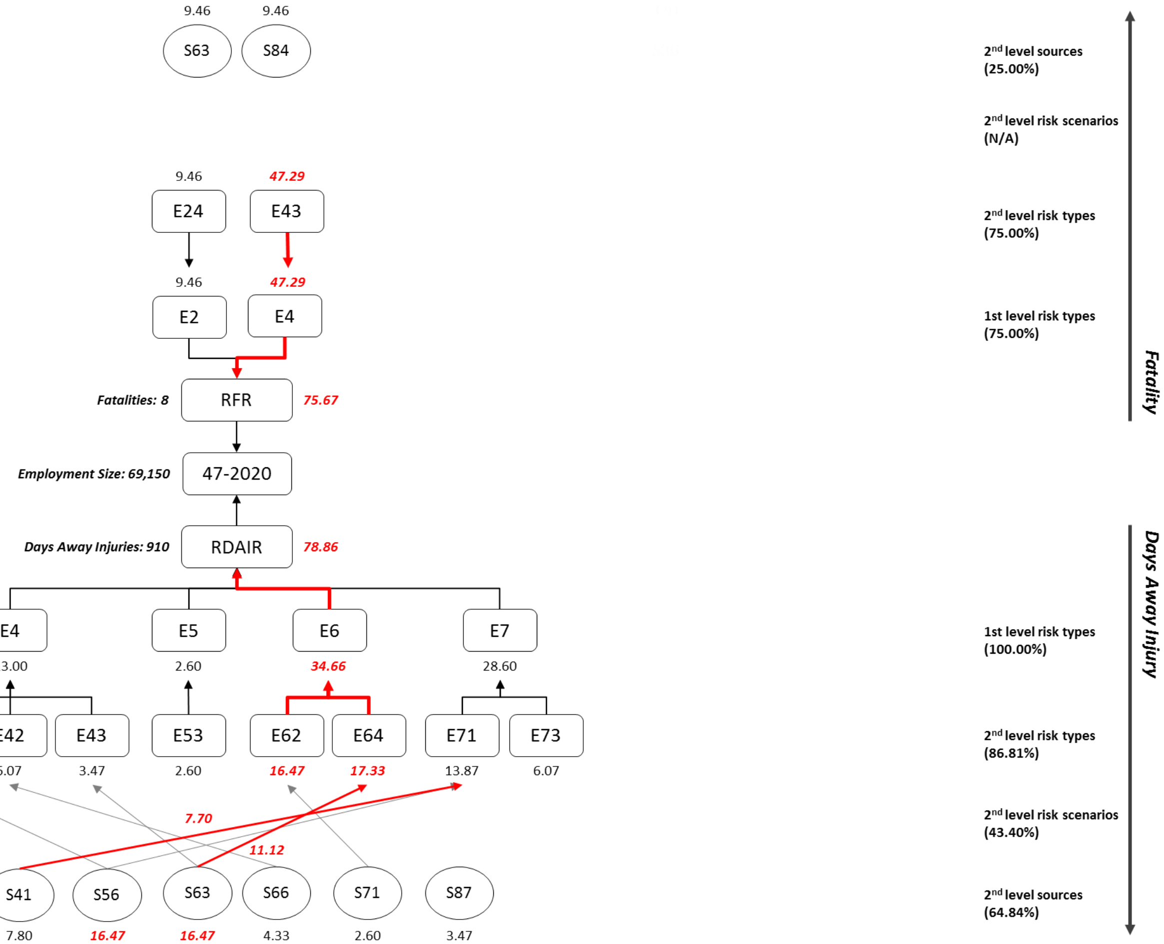


# Appendix F – Risk Quantification Model

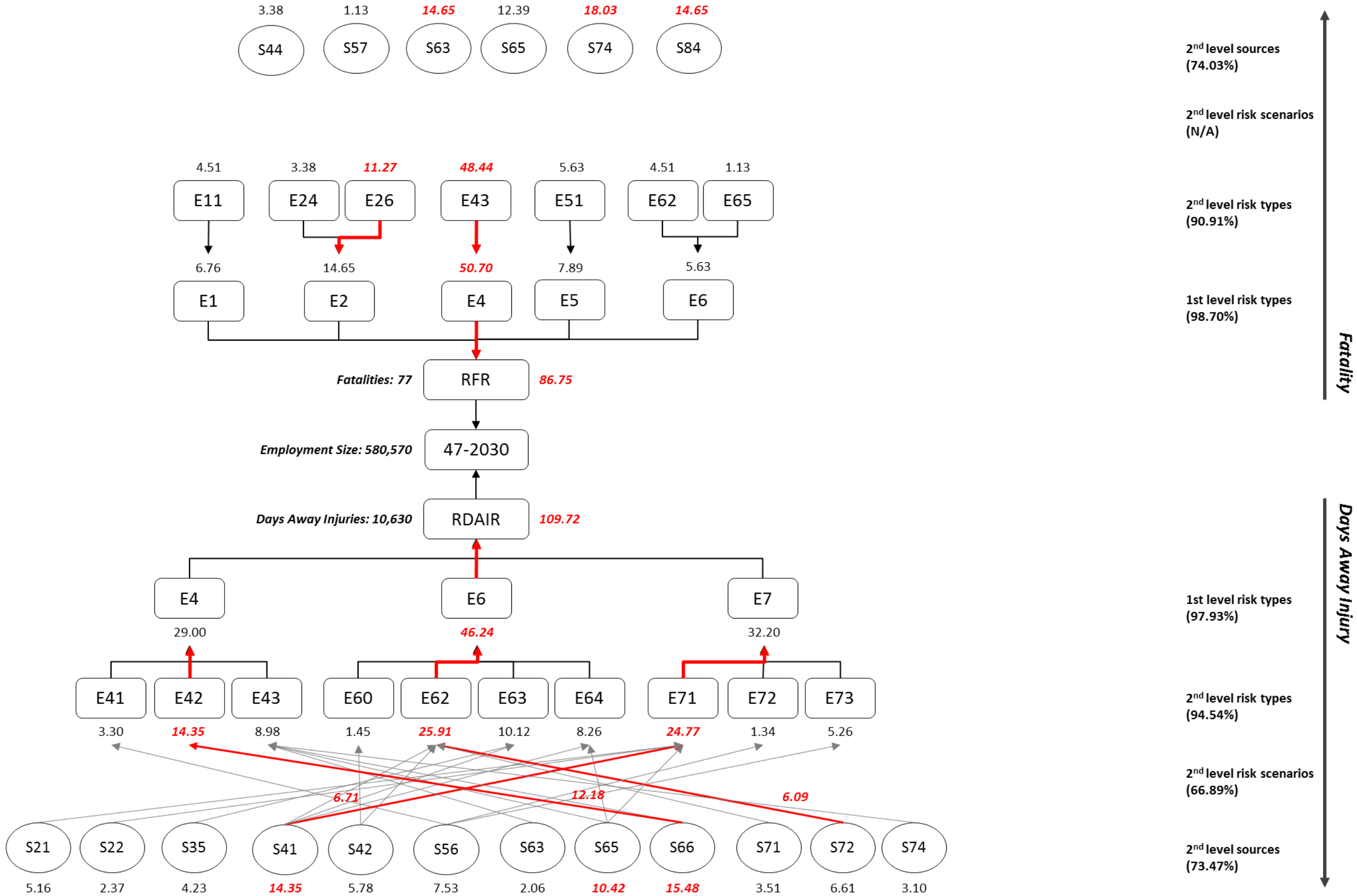
## F.1 Construction Trades Workers (47-2000)



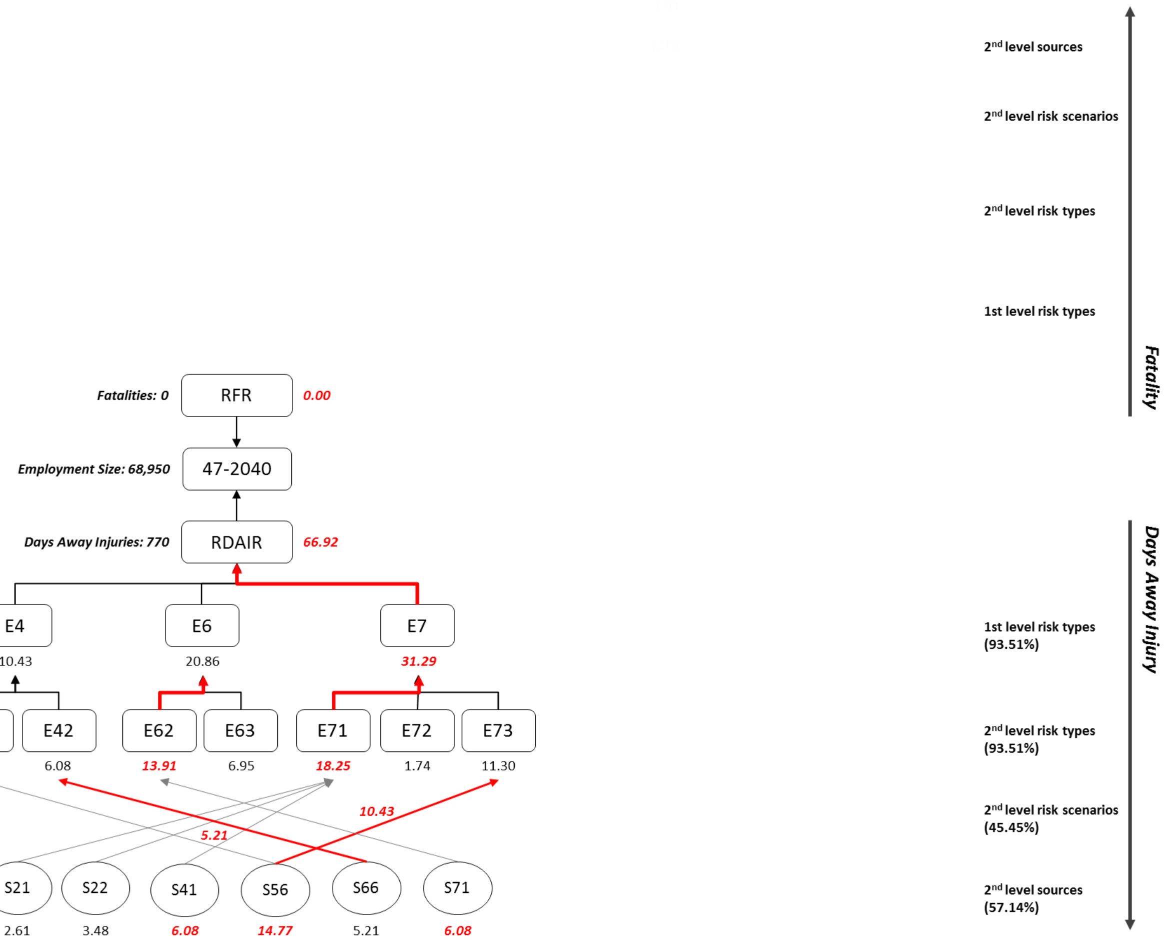
## F.2 Brickmasons, Blockmasons, and Stonemasons (47-2020)



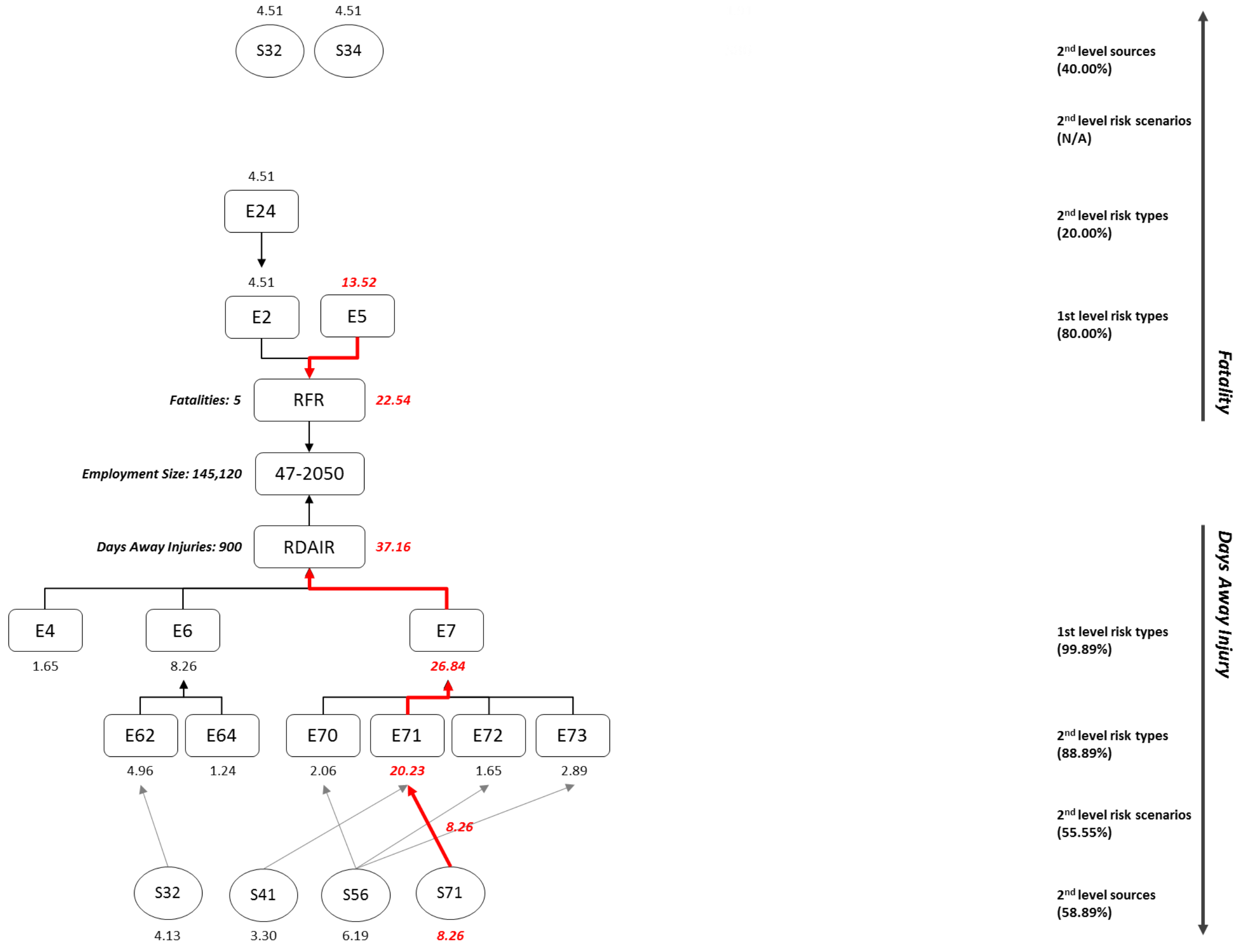
### F.3 Carpenters (47-2030)



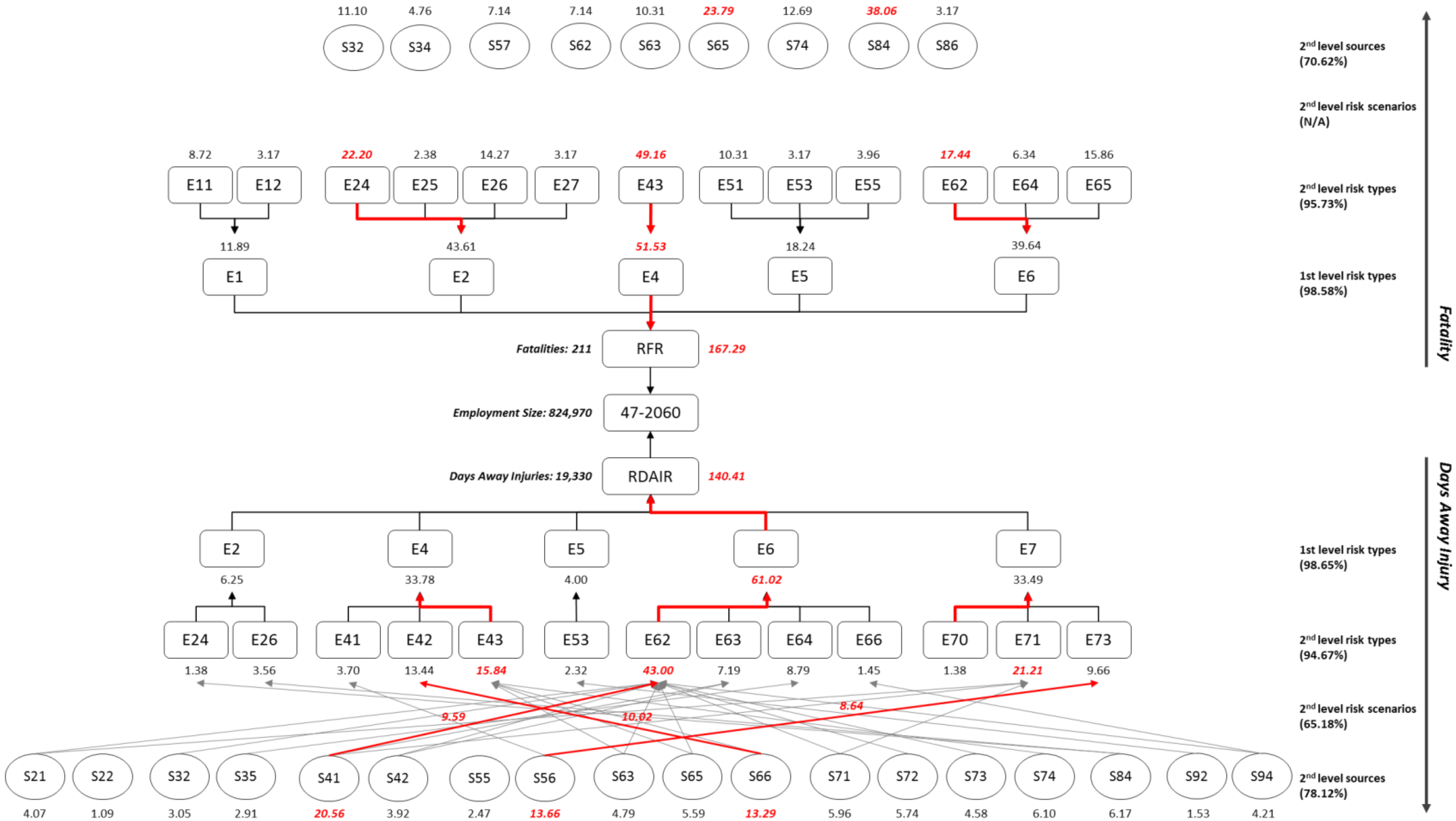
## F.4: CARPET, FLOOR, AND TILE INSTALLERS AND FINISHERS (47-2040)



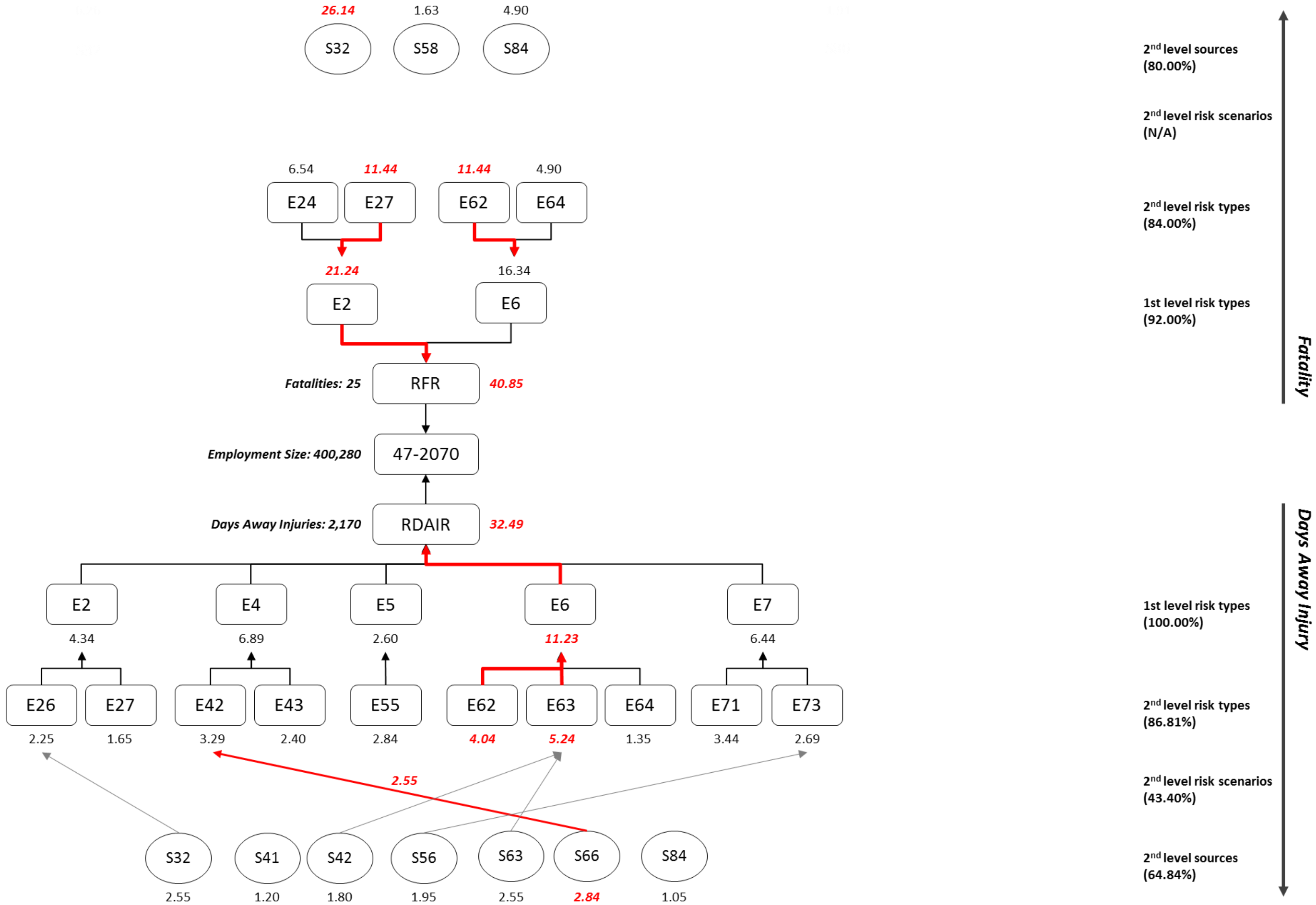
## F.5 Cement Masons, Concrete Finishers, and Terrazzo Workers (47-2050)



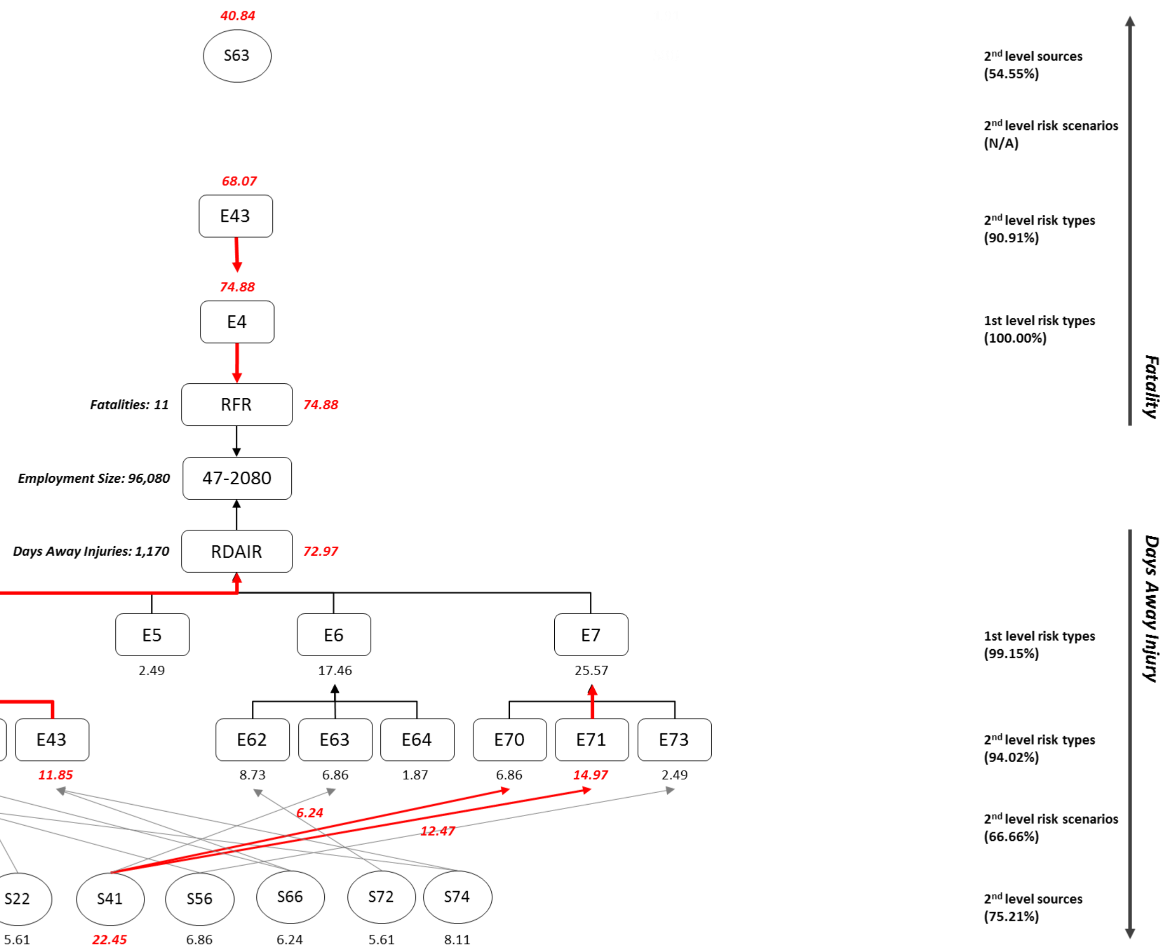
## F.6 CONSTRUCTION LABORERS (47-2060)



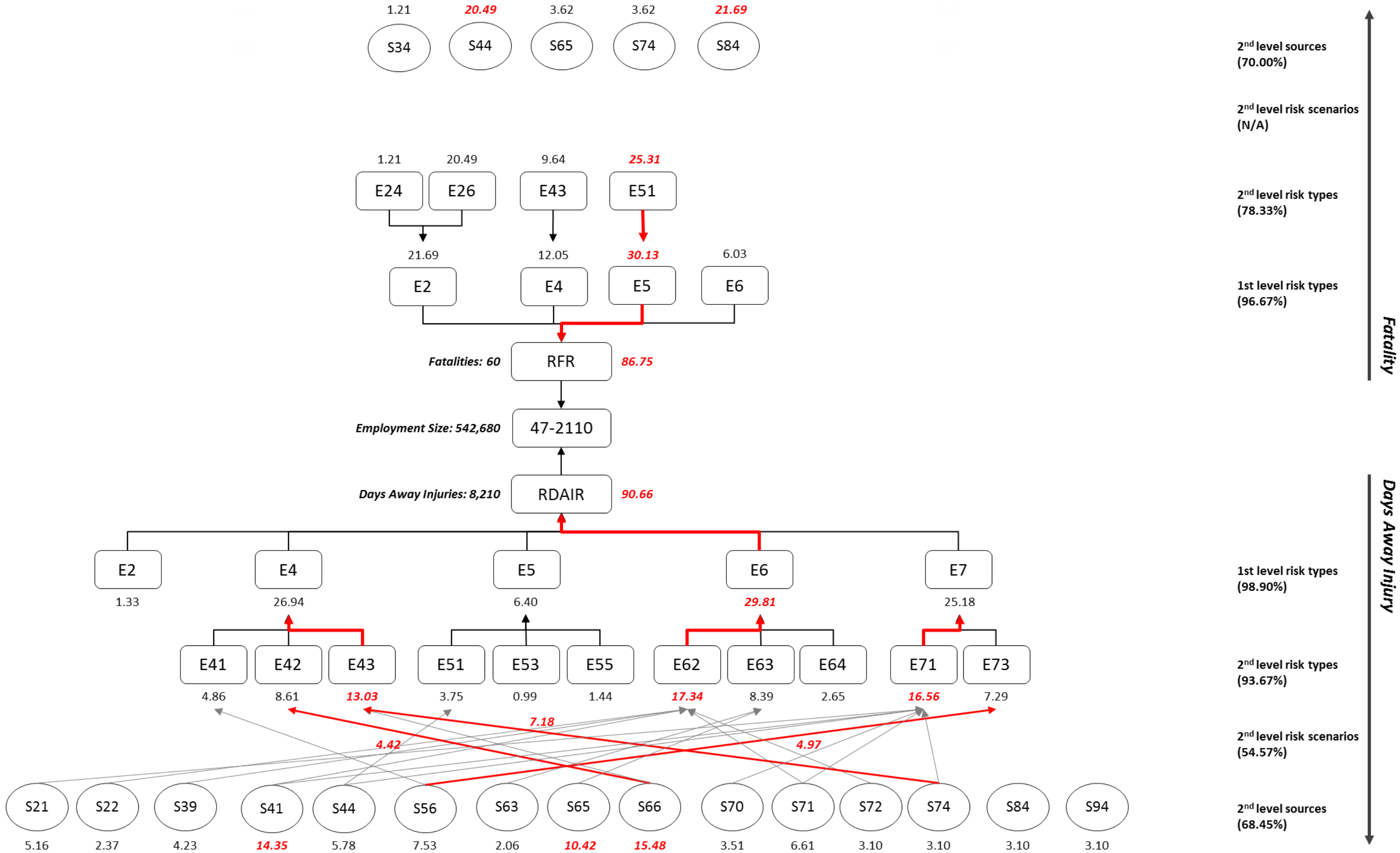
## F.7 Construction Equipment Operators (47-2070)



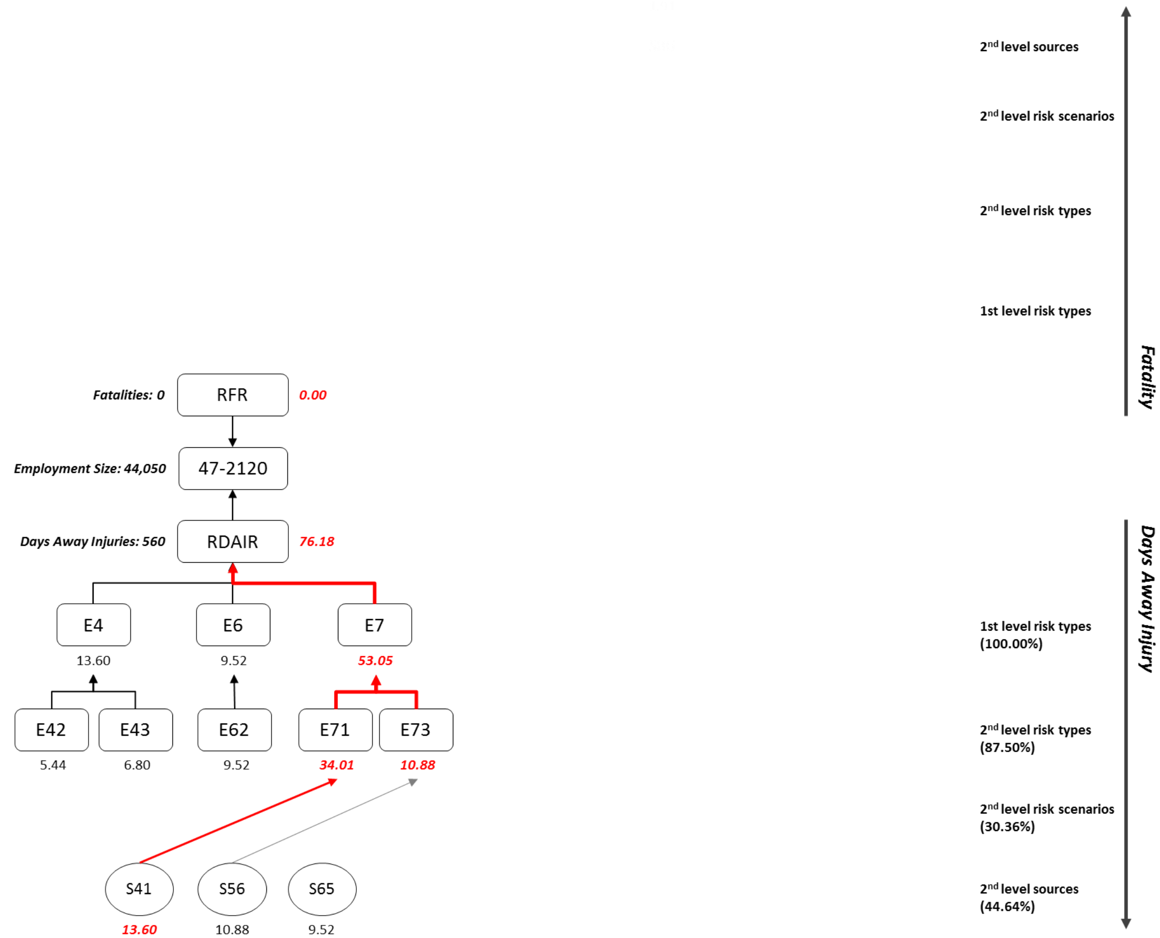
# F.8 Drywall Installers, Ceiling Tile Installers, and Tapers (47-2080)



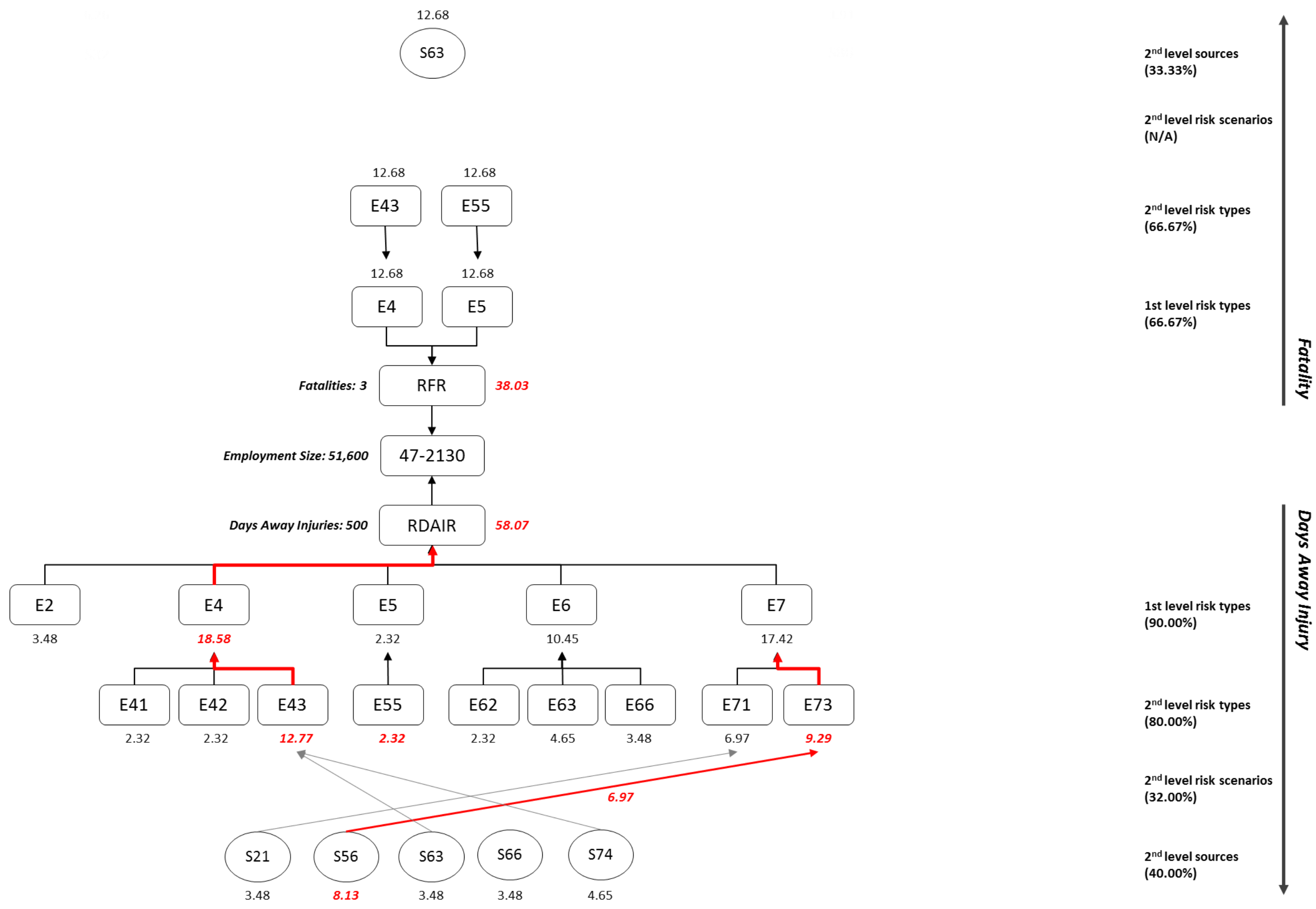
## F.9 Electricians (47-2110)



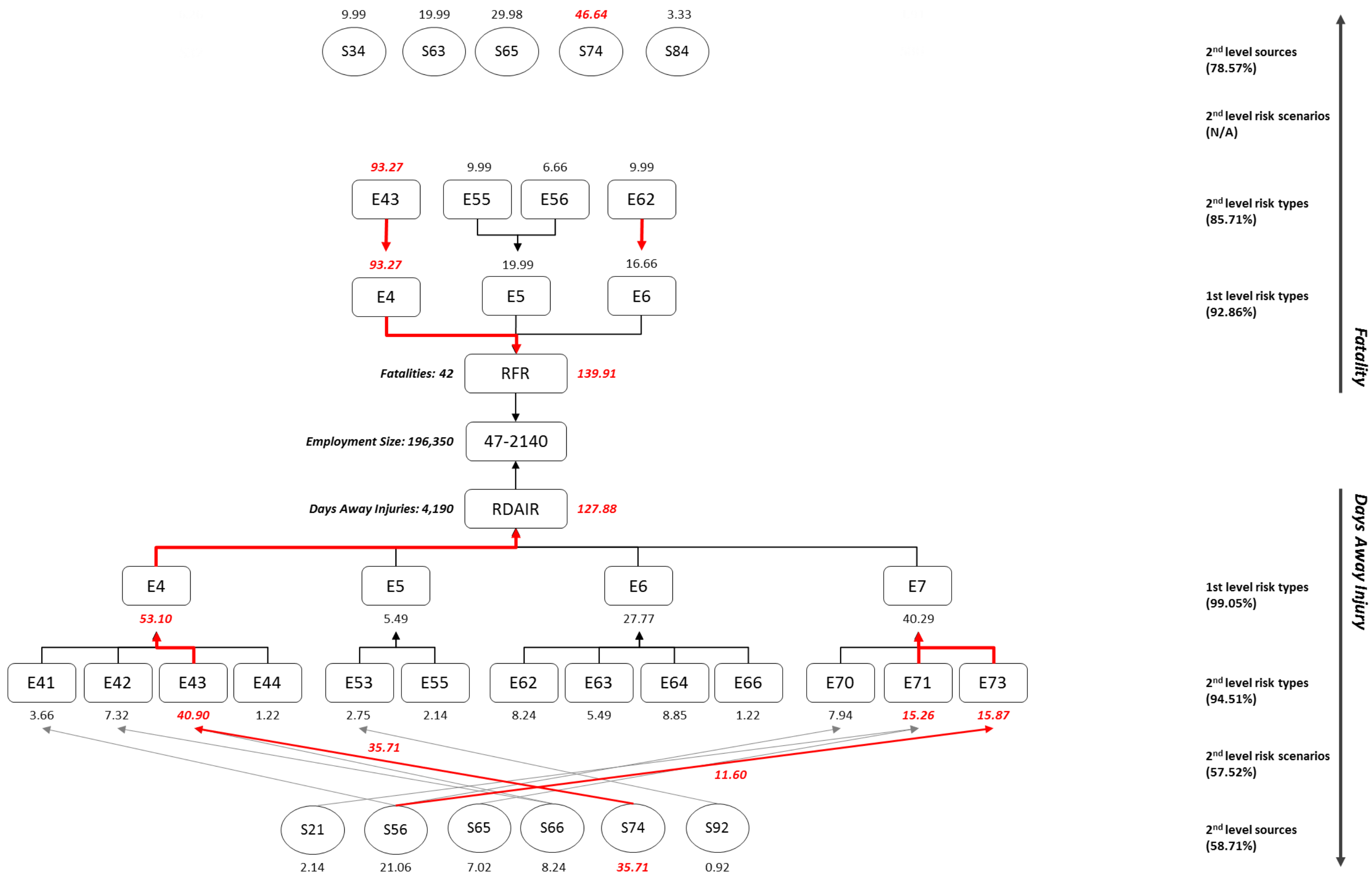
## F.10 Glaziers (47-2120)



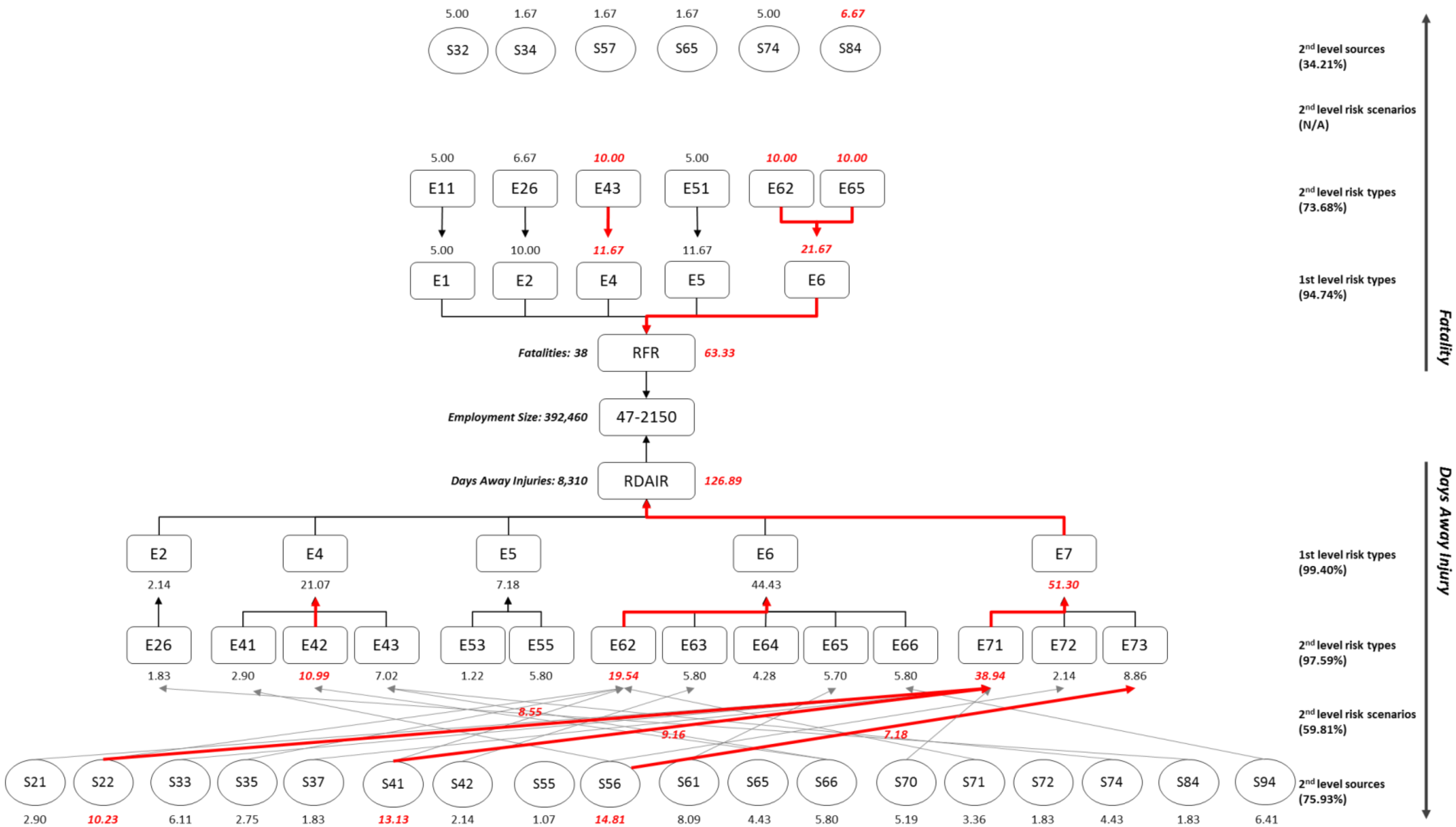
## F.11 Insulation Workers (47-2130)



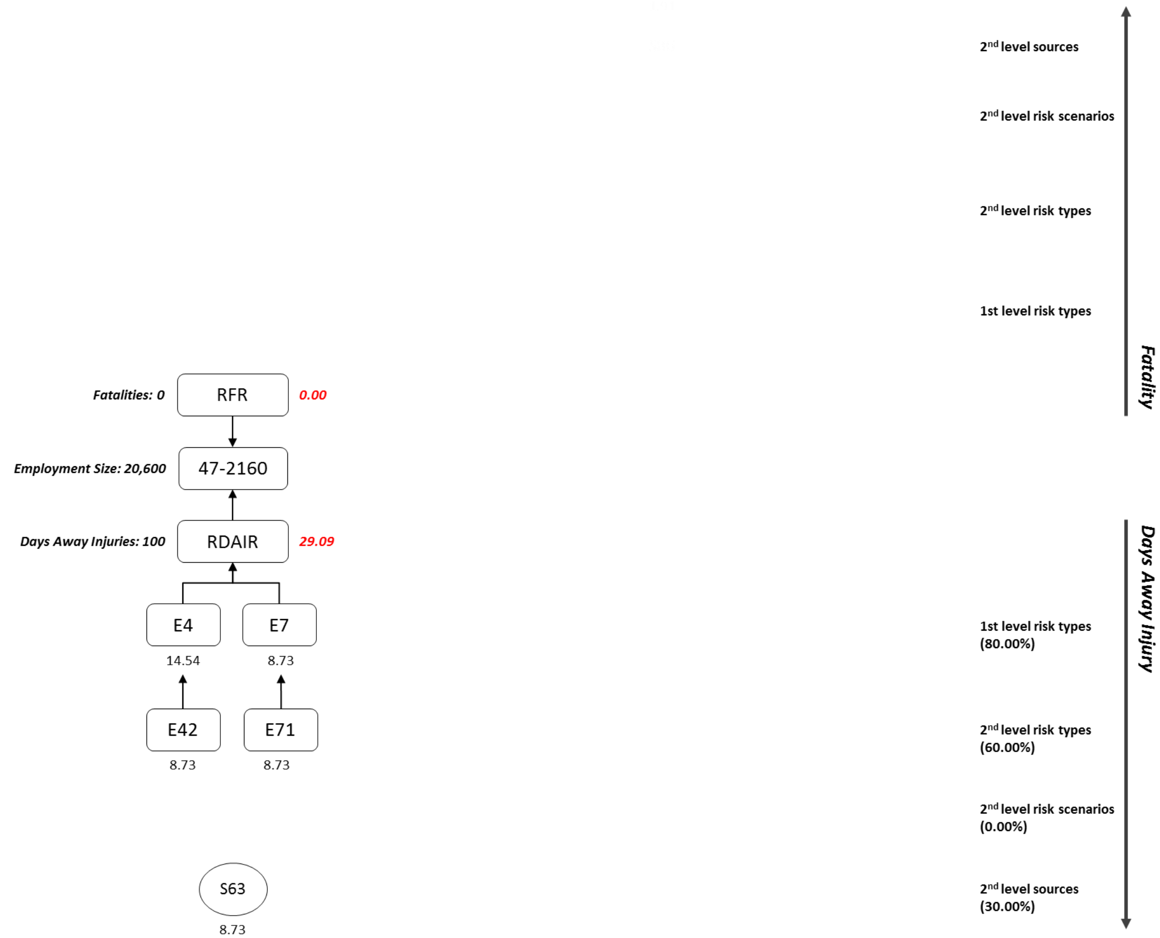
## F.12 PAINTERS AND PAPERHANGERS (47-2140)



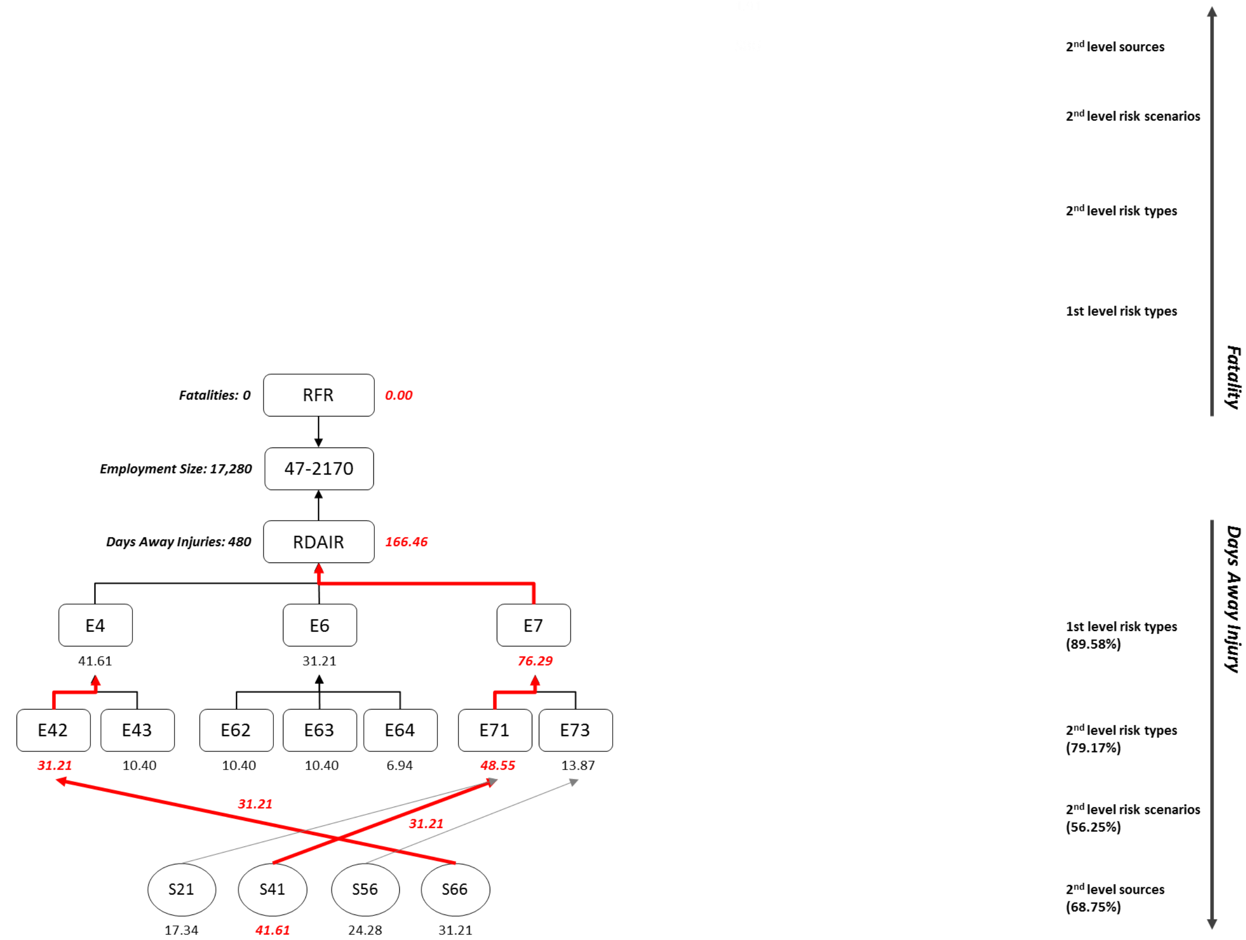
## F.13 Pipelayers, Plumbers, Pipefitters, and Steamfitters (47-2150)



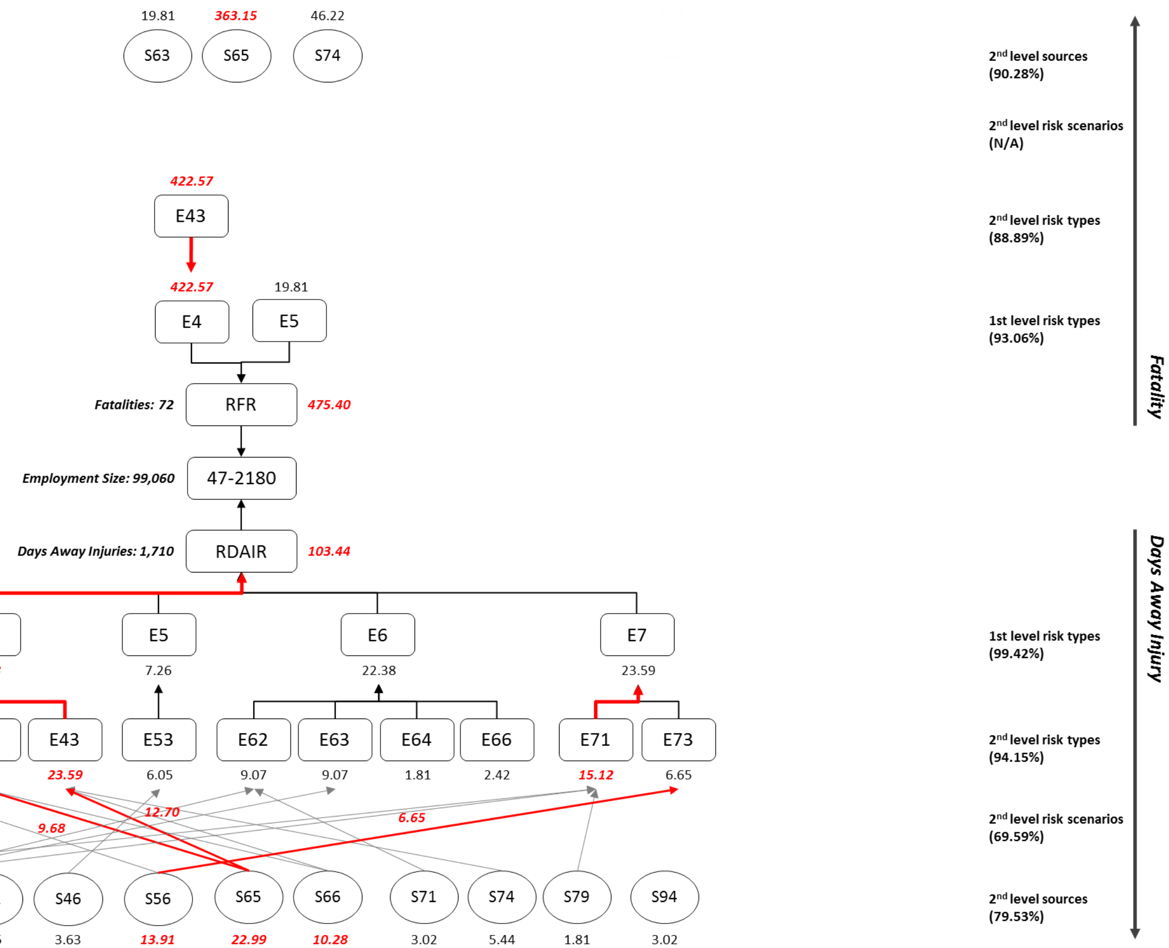
## F.14 PLASTERERS AND STUCCO MASONS (47-2160)



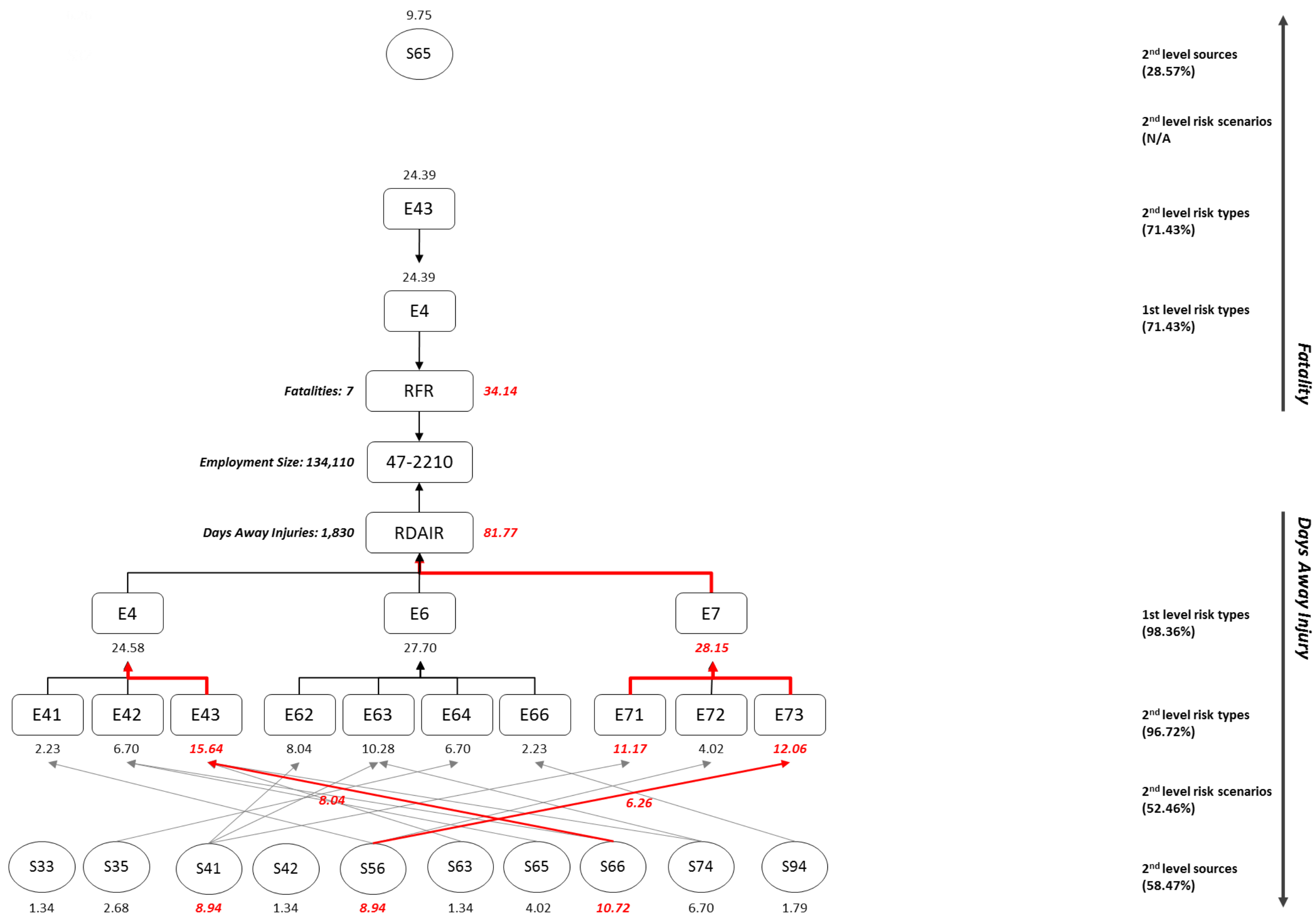
## F.15 Reinforcing Iron and Rebar Workers (47-2170)



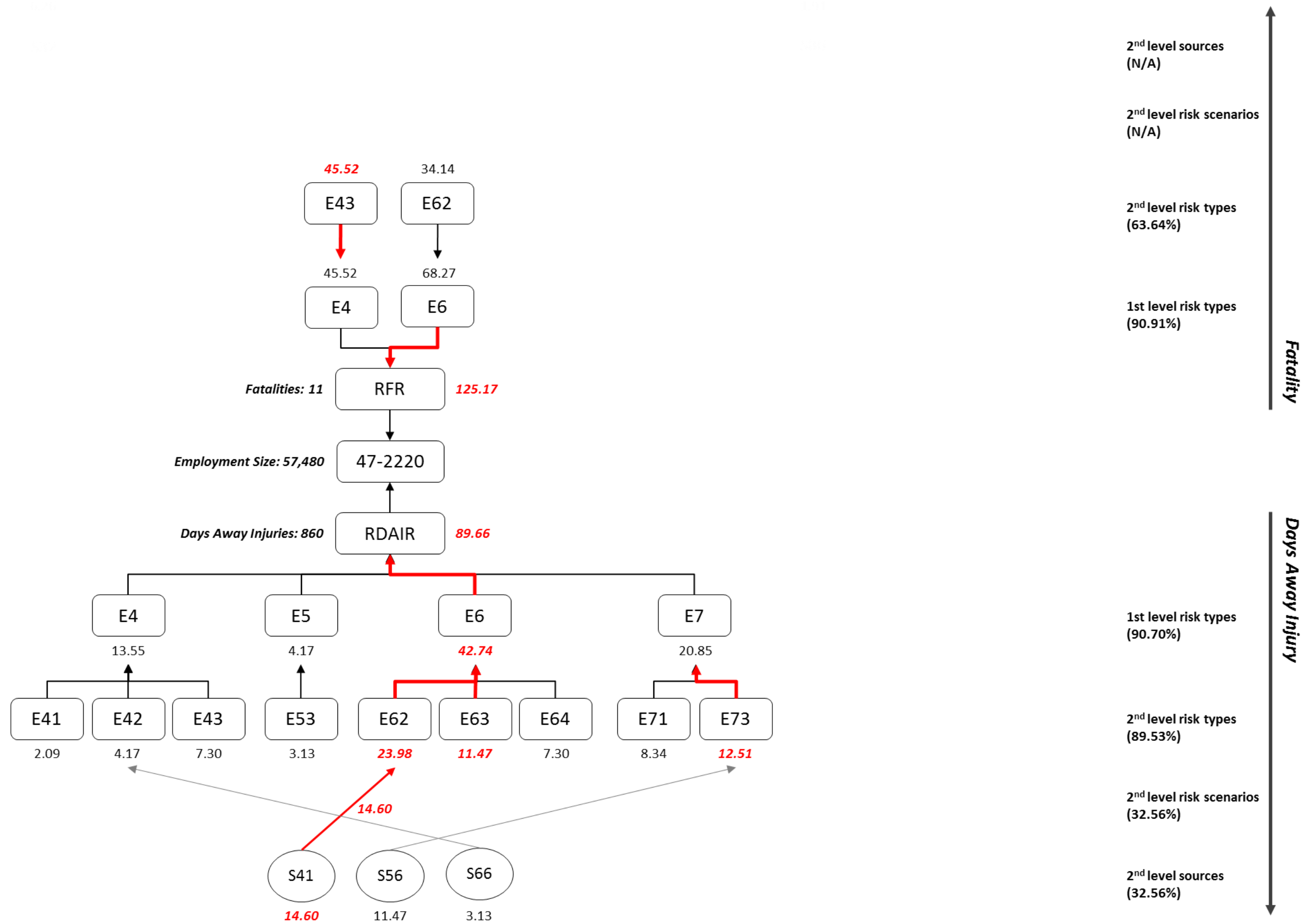
## F.16 Roofers (47-2180)



## F.17 Sheet Metal Workers (47-2210)

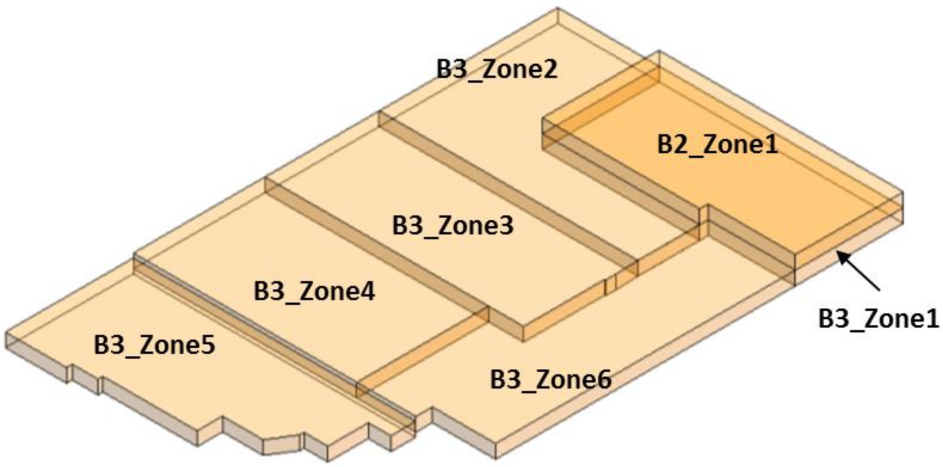


## F.18 Structural Iron and Steel Workers (47-2220)



# Appendix G – Initial Safety Analysis of Project B (Parking Garage)

## G.1 Zoning Plan



## G.2 Initial Activity Analysis

| Type | Occupation | Numer of workers | Total | | Activity Safety Score | Common Hazard Types | | | | | | | | | Common Sources of Injuires | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Fatality | | | Days Away Injury | | | Overall | | | Fatality | | | Days Away Injury | | | Overall | | |
| | | | Fatality Risk | Days away injury Risk | | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % |
| FRP Vertical Wall | Carpenter | 1 | 86.75 | 109.72 | 196.47 | E43 | 48.44 | 55.8% | E62 | 25.91 | 23.6% | E43 | 57.42 | 29.2% | S74 | 18.03 | 20.8% | S66 | 15.48 | 14.1% | S65 | 22.81 | 11.6% |
| | | | | | | E26 | 11.27 | 13.0% | E71 | 24.77 | 22.6% | E62 | 30.42 | 15.5% | S63 | 14.65 | 16.9% | S41 | 14.35 | 13.1% | S74 | 21.13 | 10.8% |
| | | | | | | E51 | 5.63 | 6.5% | E42 | 14.35 | 13.1% | E71 | 24.77 | 12.6% | S84 | 14.65 | 16.9% | S65 | 10.42 | 9.5% | S63 | 16.71 | 8.5% |
| | Total | 1 | 86.75 | 109.72 | | Representative | | 75.3% | | | 59.3% | | | 57.3% | Representative | | 54.6% | | | 36.7% | | | 30.9% |
| SOG | Laborer | 1 | 167.29 | 140.41 | 307.7 | E43 | 49.16 | 29.4% | E62 | 43 | 30.6% | E43 | 65 | 21.1% | S84 | 38.06 | 22.8% | S41 | 20.56 | 14.6% | S84 | 44.23 | 14.4% |
| | | | | | | E24 | 22.2 | 13.3% | E71 | 21.21 | 15.1% | E62 | 60.44 | 19.6% | S65 | 23.79 | 14.2% | S56 | 13.66 | 9.7% | S65 | 29.38 | 9.5% |
| | | | | | | E62 | 17.44 | 10.4% | E43 | 15.84 | 11.3% | E24 | 23.58 | 7.7% | S74 | 12.69 | 7.6% | S66 | 13.29 | 9.5% | S41 | 20.56 | 6.7% |
| | Total | 1 | 167.29 | 140.41 | | Representative | | 53.1% | | | 57.0% | | | 48.4% | Representative | | 44.6% | | | 33.8% | | | 30.6% |
| FRP Column | Carpenter | 1 | 86.75 | 109.72 | 196.47 | E43 | 48.44 | 55.8% | E62 | 25.91 | 23.6% | E43 | 57.42 | 29.2% | S74 | 18.03 | 20.8% | S66 | 15.48 | 14.1% | S65 | 22.81 | 11.6% |
| | | | | | | E26 | 11.27 | 13.0% | E71 | 24.77 | 22.6% | E62 | 30.42 | 15.5% | S63 | 14.65 | 16.9% | S41 | 14.35 | 13.1% | S74 | 21.13 | 10.8% |
| | | | | | | E51 | 5.63 | 6.5% | E42 | 14.35 | 13.1% | E71 | 24.77 | 12.6% | S84 | 14.65 | 16.9% | S65 | 10.42 | 9.5% | S63 | 16.71 | 8.5% |
| | Total | 1 | 86.75 | 109.72 | | Representative | | 75.3% | | | 59.3% | | | 57.3% | Representative | | 54.6% | | | 36.7% | | | 30.9% |
| Place Concrete | Laborer | 1 | 167.29 | 167.29 | 334.58 | E43 | 49.16 | 29.4% | E62 | 43 | 30.6% | E43 | 65 | 21.1% | S84 | 38.06 | 22.8% | S41 | 20.56 | 14.6% | S84 | 44.23 | 14.4% |
| | | | | | | E24 | 22.2 | 13.3% | E71 | 21.21 | 15.1% | E62 | 60.44 | 19.6% | S65 | 23.79 | 14.2% | S56 | 13.66 | 9.7% | S65 | 29.38 | 9.5% |
| | | | | | | E62 | 17.44 | 10.4% | E43 | 15.84 | 11.3% | E24 | 23.58 | 7.7% | S74 | 12.69 | 7.6% | S66 | 13.29 | 9.5% | S41 | 20.56 | 6.7% |
| | Total | 1 | 167.29 | 167.29 | | Representative | | 53.1% | | | 57.0% | | | 48.4% | Representative | | 44.6% | | | 33.8% | | | 30.6% |
| Form Deck | Carpenter | 1 | 86.75 | 109.72 | 196.47 | E43 | 48.44 | 55.8% | E62 | 25.91 | 23.6% | E43 | 57.42 | 29.2% | S74 | 18.03 | 20.8% | S66 | 15.48 | 14.1% | S65 | 22.81 | 11.6% |
| | | | | | | E26 | 11.27 | 13.0% | E71 | 24.77 | 22.6% | E62 | 30.42 | 15.5% | S63 | 14.65 | 16.9% | S41 | 14.35 | 13.1% | S74 | 21.13 | 10.8% |
| | | | | | | E51 | 5.63 | 6.5% | E42 | 14.35 | 13.1% | E71 | 24.77 | 12.6% | S84 | 14.65 | 16.9% | S65 | 10.42 | 9.5% | S63 | 16.71 | 8.5% |
| | Total | 1 | 86.75 | 109.72 | | Representative | | 75.3% | | | 59.3% | | | 57.3% | Representative | | 54.6% | | | 36.7% | | | 30.9% |
| Rebar/MEP Slab | Rodman | 1 | 0 | 166.46 | 166.46 | | | | E71 | 48.55 | 29.2% | E71 | 48.55 | 29.2% | | | | S41 | 41.61 | 25.0% | S41 | 41.61 | 25.0% |
| | | | | | | | | | E42 | 31.21 | 18.7% | E42 | 31.21 | 18.7% | | | | S66 | 31.21 | 18.7% | S66 | 31.21 | 18.7% |
| | | | | | | | | | E73 | 13.87 | 8.3% | E73 | 13.87 | 8.3% | | | | S56 | 24.28 | 14.6% | S56 | 24.28 | 14.6% |
| | Total | 1 | 0 | 166.46 | | Representative | | 0.0% | | | 56.2% | | | 56.2% | Representative | | 0.0% | | | 58.3% | | | 58.3% |

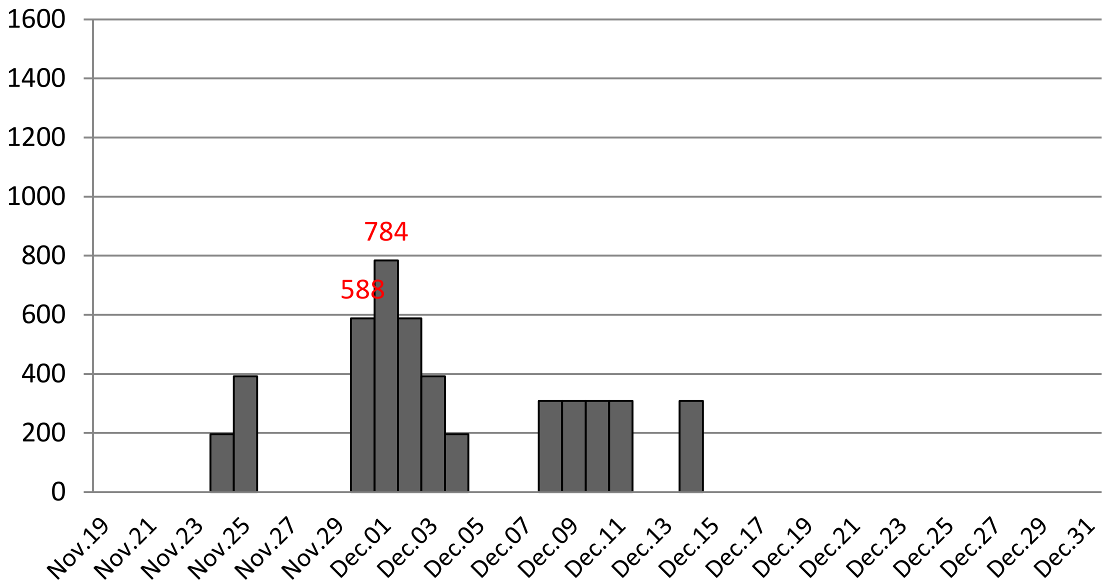
## G.3 Initial Work Period Analysis

| Date | Safety Score | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 1454 | FRP Vertical Walls Level B3-W7 | 196 | E43 | 362.5 | 24.9% | S65 | 143.43 | 9.9% |
| | | FRP Vertical Walls Level B3-W6 | 196 | E62 | 222.94 | 15.3% | S41 | 133.92 | 9.2% |
| | | FRP Vertical Walls Level B3-S1 | 196 | E71 | 193.61 | 13.3% | S74 | 124.44 | 8.6% |
| | | SOG Pour 2 | 308 | | | | | | |
| | | FRP Columns Level B3 (in SOG3) | 196 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 166 | | | | | | |
| | | Form Deck Level B2 Pour 1 | 196 | Representative | | 53.6% | Representative | | 27.6% |
| 12/23/2015 | 1260.04 | FRP Vertical Walls Level B3-W7 | 196.47 | E43 | 305.08 | 24.2% | S65 | 120.62 | 9.6% |
| | | FRP Vertical Walls Level B3-S2 | 196.47 | E62 | 192.52 | 15.3% | S41 | 119.57 | 9.5% |
| | | FRP Vertical Walls Level B3-S3 | 196.47 | E71 | 168.84 | 13.4% | S66 | 106.42 | 8.4% |
| | | SOG Pour 3 | 307.7 | | | | | | |
| | | FRP Columns Level B3 (in SOG4) | 196.47 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 166.46 | Representative | | 52.9% | Representative | | 27.5% |
| 12/28/2015 | 1204.81 | FRP Vertical Walls Level B3-S2 | 196.47 | E43 | 302.26 | 25.1% | S84 | 132.41 | 11.0% |
| | | FRP Vertical Walls Level B3-S4 | 196.47 | E62 | 212.14 | 17.6% | S65 | 127.19 | 10.6% |
| | | SOG Pour 3 | 307.7 | E71 | 116.73 | 9.7% | S74 | 100.97 | 8.4% |
| | | FRP Columns Level B3 (in SOG4) | 196.47 | | | | | | |
| | | Place Concrete Level B2 Pour 1 | 307.7 | Representative | | 52.4% | Representative | | 29.9% |
| 12/29/2015 | 1093.58 | FRP Vertical Walls Level B3-S2 | 196.47 | E43 | 294.68 | 24.5% | S65 | 120.62 | 10.0% |
| | | FRP Vertical Walls Level B3-S4 | 196.47 | E62 | 182.12 | 15.1% | S74 | 103.31 | 8.6% |
| | | SOG Pour 3 | 307.7 | E71 | 120.29 | 10.0% | S84 | 102.83 | 8.5% |
| | | FRP Columns Level B3 (in SOG4) | 196.47 | | | | | | |
| | | FRP Columns Level B2 Pour 1 | 196.47 | Representative | | 49.6% | Representative | | 27.1% |

## G.4 Initial Work Zone Safety Analysis

### G.4.1 Basement 3_Zone 1

- Safety score profile for B3_Zone1

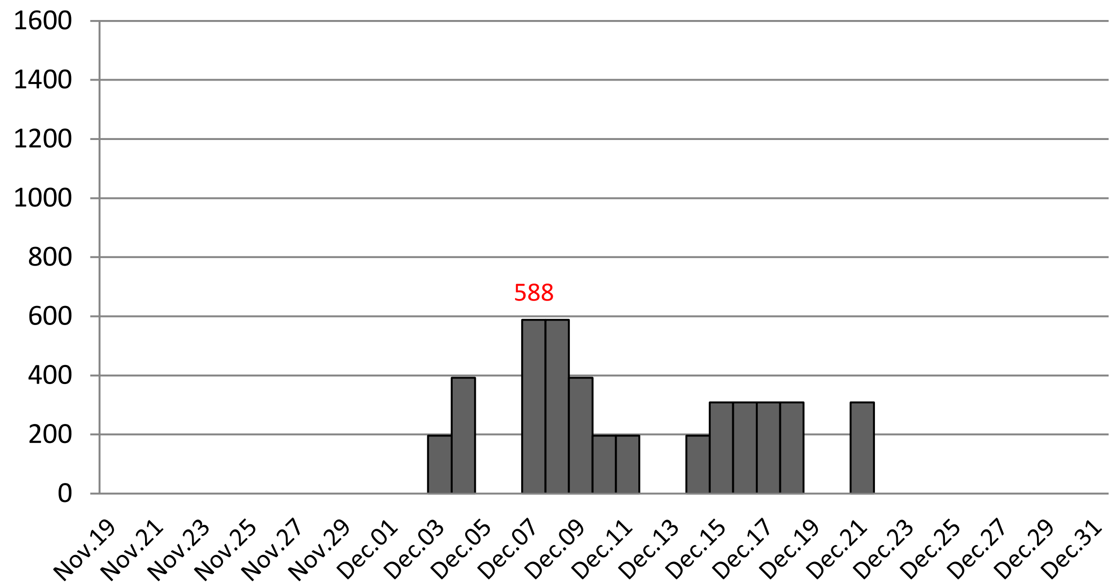



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/1/2015 | 784 | FRP Vertical Walls Level B3-E1 | 196 | E43 | 229.68 | 29.3% | S65 | 91.24 | 11.6% |
| | | FRP Vertical Walls Level B3-N4 | 196 | E62 | 121.68 | 15.5% | S74 | 84.52 | 10.8% |
| | | FRP Vertical Walls Level B3-N3 | 196 | E71 | 99.08 | 12.6% | S63 | 66.84 | 8.5% |
| | | FRP Columns Level B3 (in SOG1) | 196 | | | | | | |
| | | | | | | 57.5% | | | 30.9% |
| 11/30/2015 | 588 | FRP Vertical Walls Level B3-E1 | 196 | E43 | 172.26 | 29.3% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-N4 | 196 | E62 | 91.26 | 15.5% | S74 | 63.39 | 10.8% |
| | | FRP Vertical Walls Level B3-EW1 | 196 | E71 | 74.31 | 12.6% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

## G.4.2 Basement 3_Zone 2

- Safety score profile for B3_Zone2

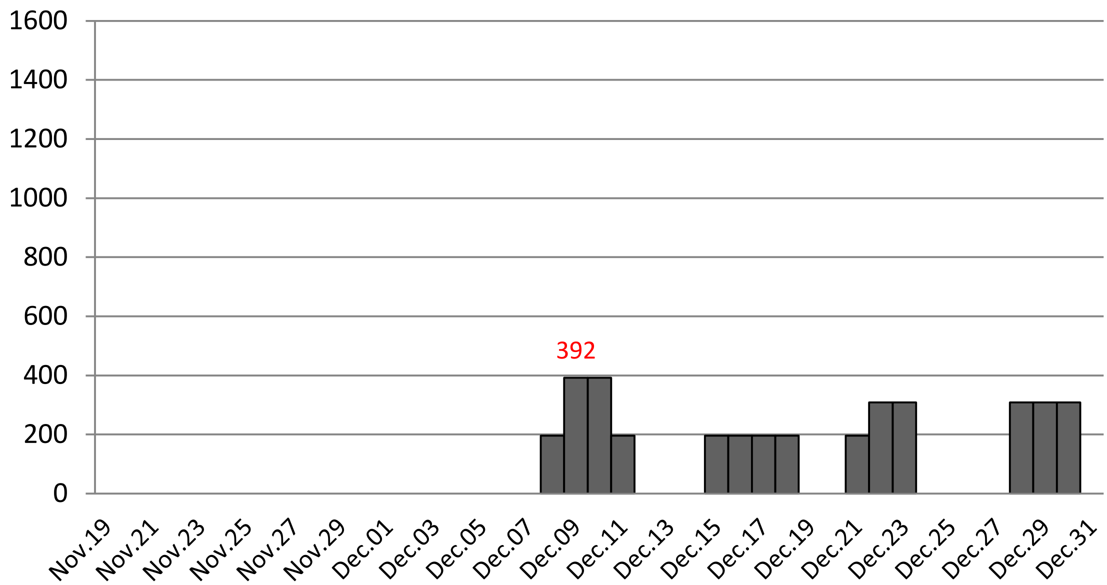



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/7/2015 | 588 | FRP Vertical Walls Level B3-W1 | 196 | E43 | 172.26 | 22.0% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-N1 | 196 | E62 | 91.26 | 11.6% | S74 | 63.39 | 10.8% |
| | | FRP Vertical Walls Level B3-W2 | 196 | E71 | 74.31 | 9.5% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 43.1% | | | 30.9% |
| 12/8/2015 | 588 | FRP Vertical Walls Level B3-W1 | 196 | E43 | 172.26 | 29.3% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-W2 | 196 | E62 | 91.26 | 15.5% | S74 | 63.39 | 10.8% |
| | | FRP Columns Level B3 (in SOG2) | 196 | E71 | 74.31 | 12.6% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

### G.4.3 Basement 3_Zone 3

- Safety score profile for B3_Zone3

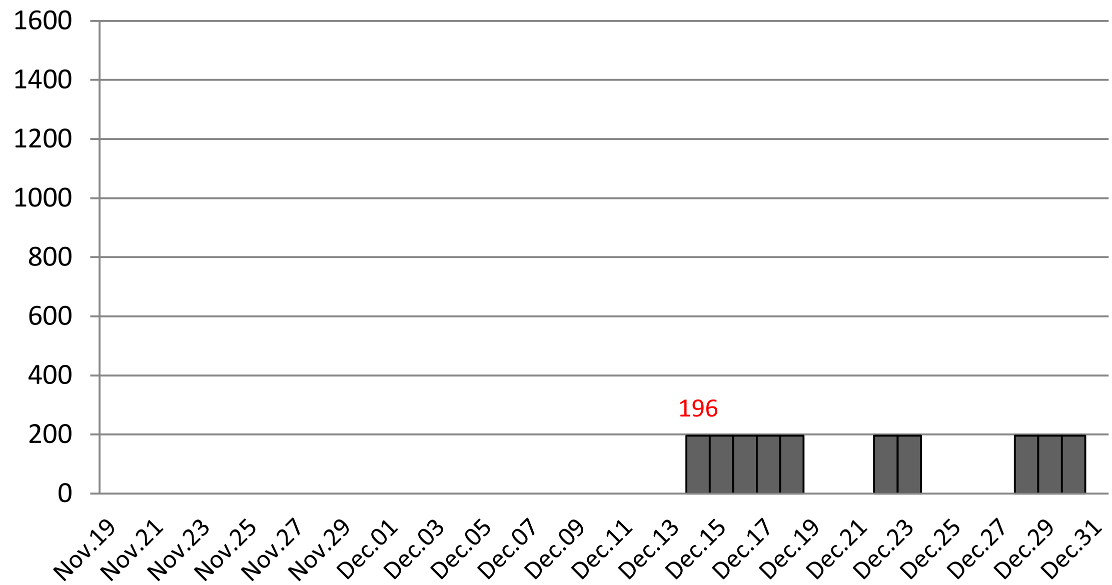



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/9/2015 | 392 | FRP Vertical Walls Level B3-W4 | 196 | E43 | 114.84 | 29.3% | S65 | 45.62 | 11.6% |
| | | FRP Vertical Walls Level B3-W3 | 196 | E62 | 60.84 | 15.5% | S74 | 42.26 | 10.8% |
| | | | | E71 | 49.54 | 12.6% | S63 | 33.42 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |
| 12/10/2015 | 392 | FRP Vertical Walls Level B3-W4 | 196 | E43 | 114.84 | 29.3% | S65 | 45.62 | 11.6% |
| | | FRP Vertical Walls Level B3-W3 | 196 | E62 | 60.84 | 15.5% | S74 | 42.26 | 10.8% |
| | | | | E71 | 49.54 | 12.6% | S63 | 33.42 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

## G.4.4 Basement 3_Zone 4

- Safety score profile for B3_Zone4

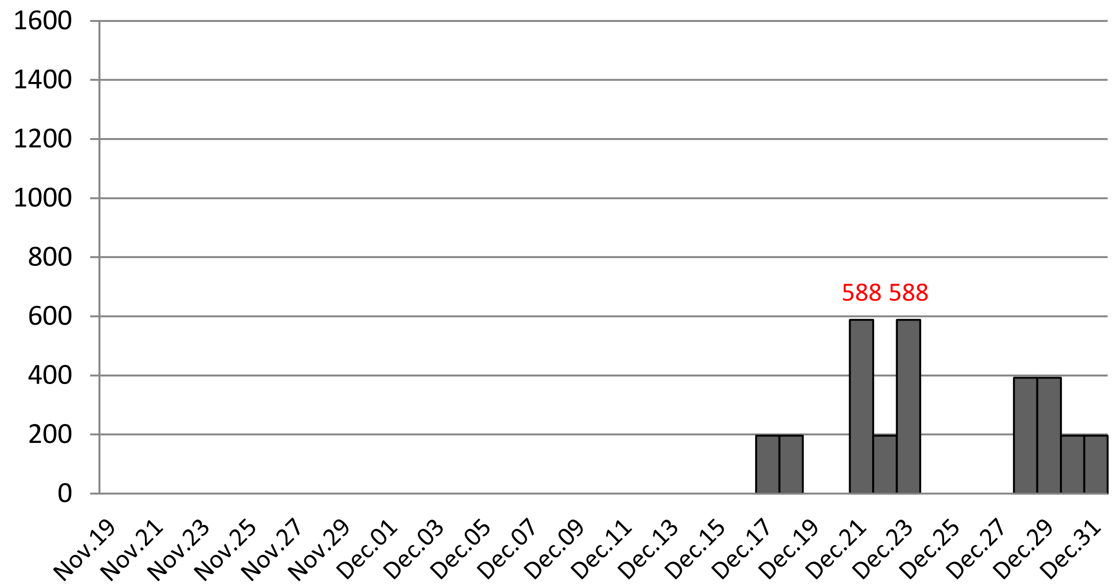



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/14/2015 | 196 | FRP Vertical Walls Level B3-W5 | 196 | E43 | 57.42 | 29.3% | S65 | 22.81 | 11.6% |
| | | | | E62 | 30.42 | 15.5% | S74 | 21.13 | 10.8% |
| | | | | E71 | 24.77 | 12.6% | S63 | 16.71 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |
| 12/22/2015 | 196 | FRP Columns Level B3 (in SOG4) | 196 | E43 | 57.42 | 29.3% | S65 | 22.81 | 11.6% |
| | | | | E62 | 30.42 | 15.5% | S74 | 21.13 | 10.8% |
| | | | | E71 | 24.77 | 12.6% | S63 | 16.71 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

### G.4.5 Basement 3_Zone 5

- Safety score profile for B3_Zone5

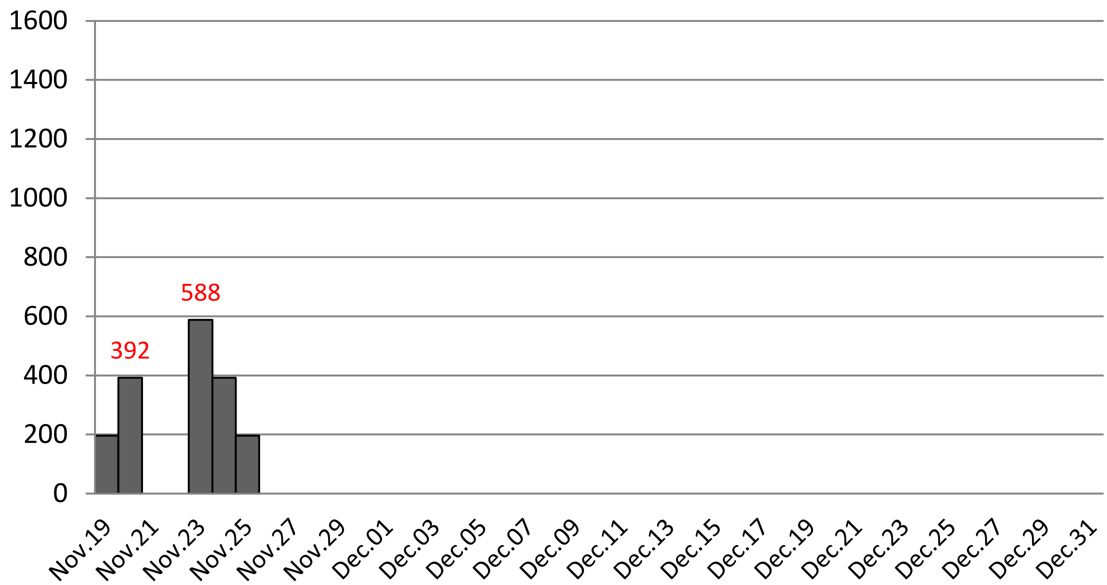



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 588 | FRP Vertical Walls Level B3-W7 | 196 | E43 | 172.26 | 29.3% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-W6 | 196 | E62 | 91.26 | 15.5% | S74 | 63.39 | 10.8% |
| | | FRP Vertical Walls Level B3-S1 | 196 | E71 | 74.31 | 12.6% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |
| 11/23/2015 | 588 | FRP Vertical Walls Level B3-W7 | 196 | E43 | 172.26 | 29.3% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-S2 | 196 | E62 | 91.26 | 15.5% | S74 | 63.39 | 10.8% |
| | | FRP Vertical Walls Level B3-S3 | 196 | E71 | 74.31 | 12.6% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

### G.4.6 Basement 3_Zone 6

- Safety score profile for B3_Zone6

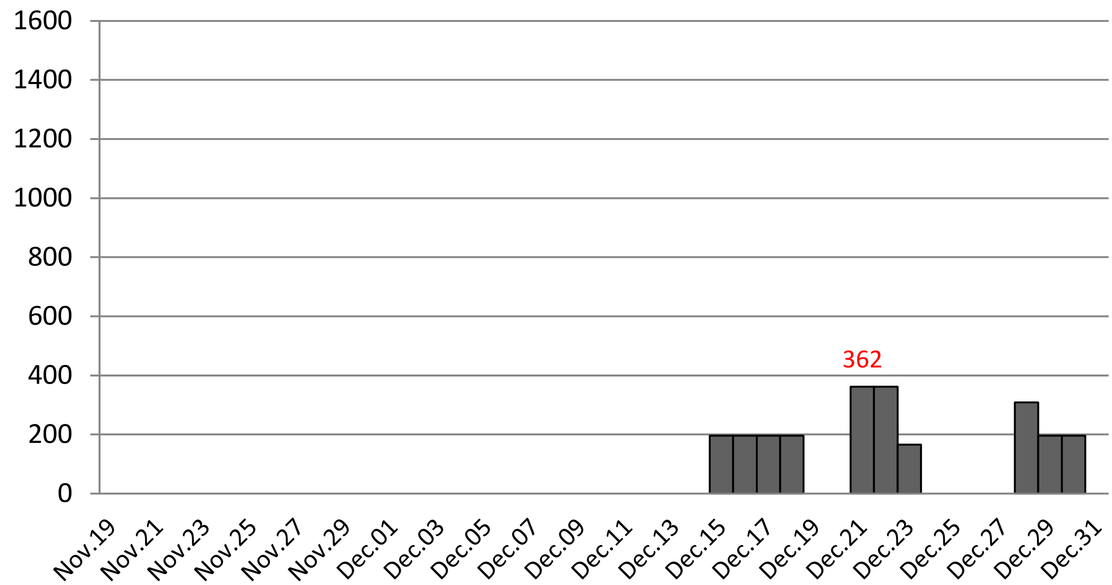



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 11/20/2015 | 392 | FRP Vertical Walls Level B3-E4 | 196 | E43 | 114.84 | 29.3% | S65 | 45.62 | 11.6% |
| | | FRP Vertical Walls Level B3-E3 | 196 | E62 | 60.84 | 15.5% | S74 | 42.26 | 10.8% |
| | | | | E71 | 49.54 | 12.6% | S63 | 33.42 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |
| 11/23/2015 | 588 | FRP Vertical Walls Level B3-E2 | 196 | E43 | 172.26 | 29.3% | S65 | 68.43 | 11.6% |
| | | FRP Vertical Walls Level B3-E4 | 196 | E62 | 91.26 | 15.5% | S74 | 63.39 | 10.8% |
| | | FRP Vertical Walls Level B3-E3 | 196 | E71 | 74.31 | 12.6% | S63 | 50.13 | 8.5% |
| | | | | | | | | | |
| | | | | | | 57.5% | | | 30.9% |

### G.4.7 Basement 2_Zone 1

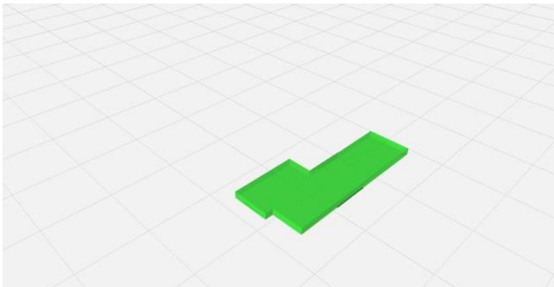
- Safety risk profile for B2_Zone1



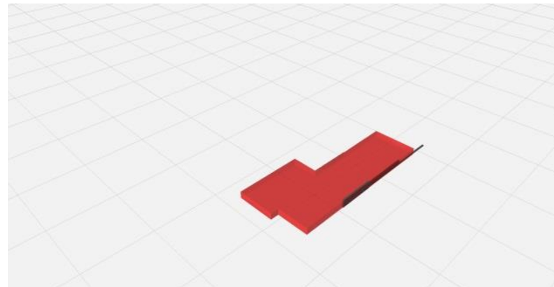

- Safety risk analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 362 | Rebar/MEP Slab Rough Level B2 Po | 166 | E71 | 73.32 | 20.3% | S41 | 55.96 | 15.5% |
| | | Form Deck Level B2 Pour 1 | 196 | E43 | 67.82 | 18.7% | S66 | 46.69 | 12.9% |
| | | | | E42 | 45.56 | 12.6% | S56 | 31.81 | 8.8% |
| | | | | | | | | | |
| | | | | | | 51.6% | | | 37.1% |
| 12/22/2015 | 362 | Rebar/MEP Slab Rough Level B2 Po | 166 | E71 | 73.32 | 20.3% | S41 | 55.96 | 15.5% |
| | | Form Deck Level B2 Pour 1 | 196 | E43 | 67.82 | 18.7% | S66 | 46.69 | 12.9% |
| | | | | E42 | 45.56 | 12.6% | S56 | 31.81 | 8.8% |
| | | | | | | | | | |
| | | | | | | 51.6% | | | 37.1% |

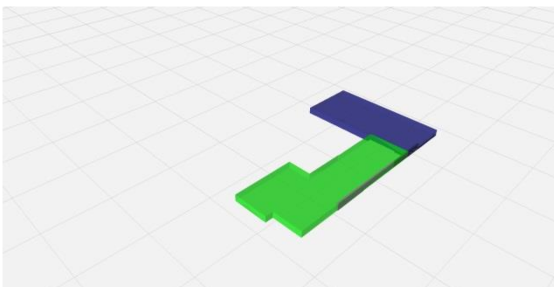
### G.5 Screen Shots of Safety 4D Simulation



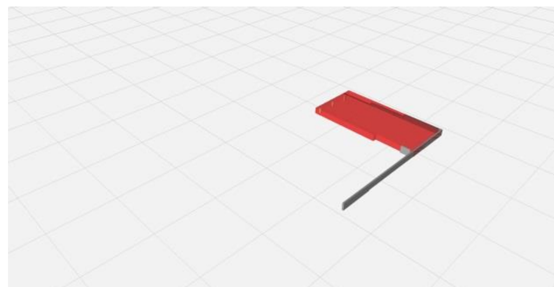
11/19/2015



11/23/2015

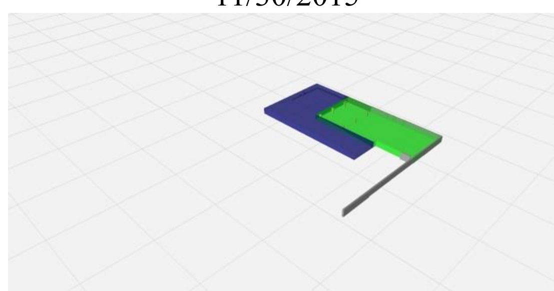


11/25/2015

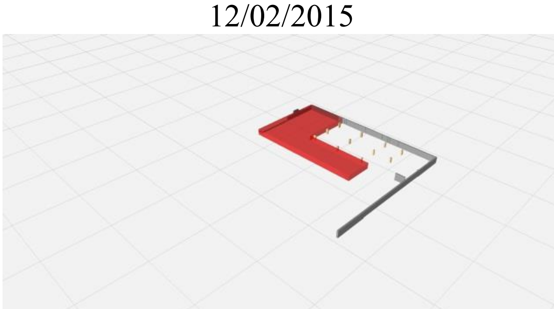


11/30/2015

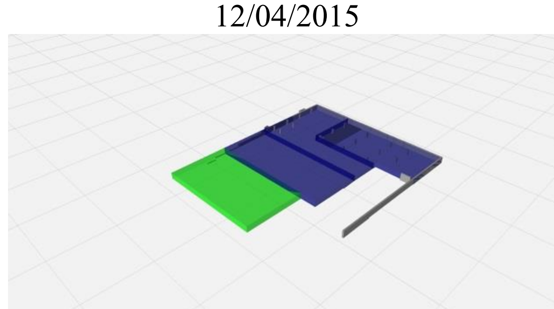
12/02/2015



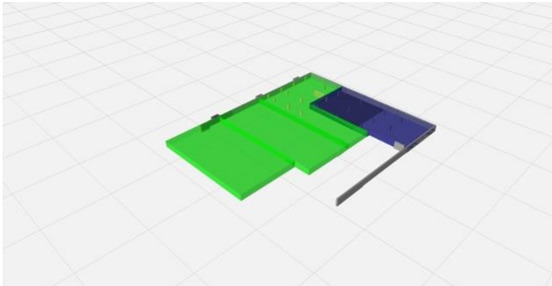
12/04/2015



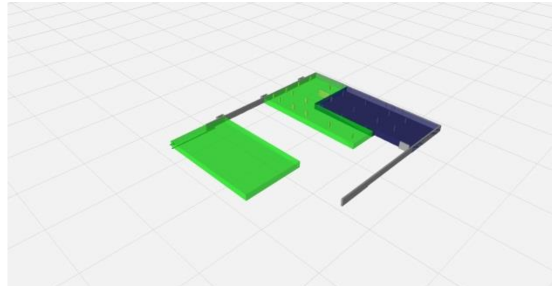
12/07/2015



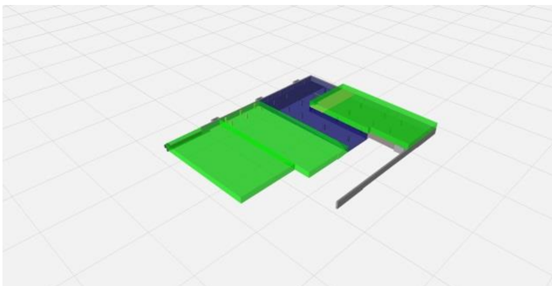
12/09/2015



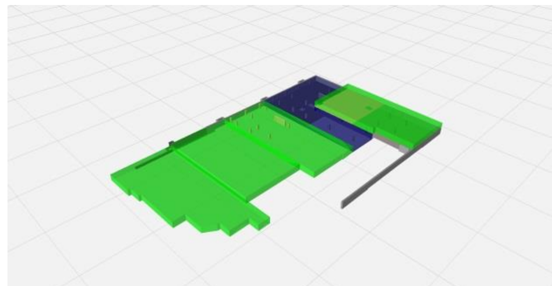
12/11/2015



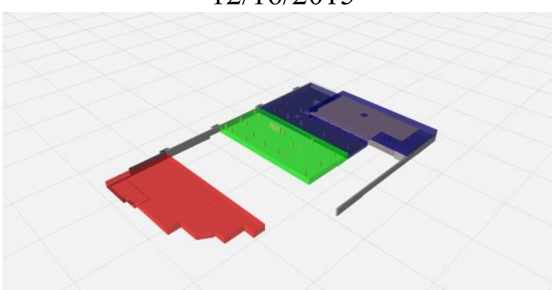
12/14/2015



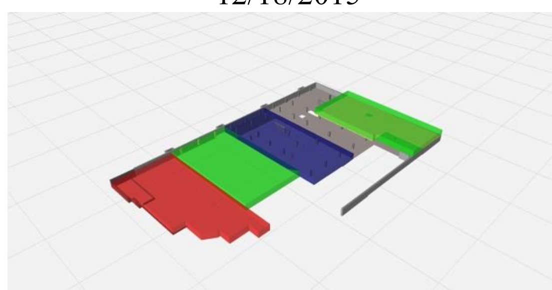
12/16/2015



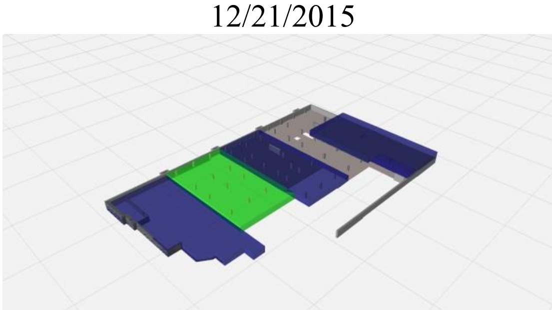
12/18/2015



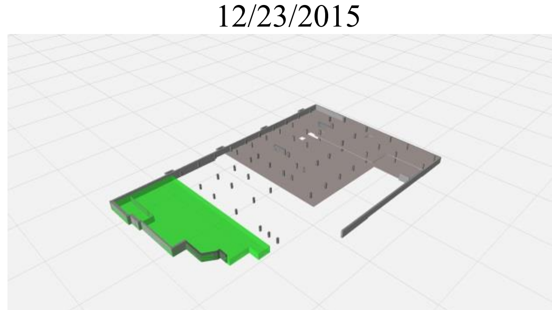
12/21/2015



12/23/2015



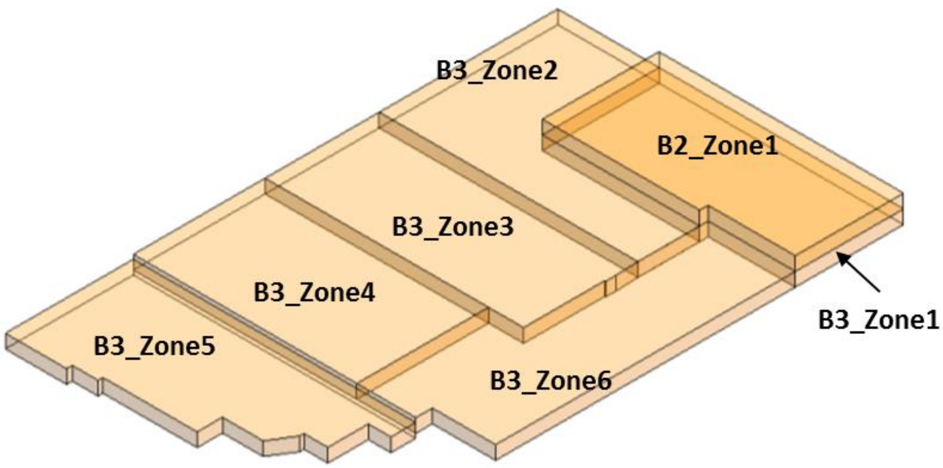
12/28/2015



12/31/2015

# Appendix I – Final Safety Analysis of Project B (Parking Garage)

## I.1 ZONING PLAN



# I.2 Final Activity Analysis

| Type | Occupation | Number of workers | Individual | | Total | | Activity Safety Score | Common Hazard Types | | | | | | | | | Common Sources of Injuires | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Fatality | | | Days Away Injury | | | Total | | | Fatality | | | Days Away Injury | | | Total | | |
| | | | Fatality Risk | Days away injury Risk | Fatality | Days away injury | | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % | Type | Amount | % |
| FRP Vertical Wall | Carpenter | 6 | 86.75 | 109.72 | 520.5 | 658.32 | 4404.82 | E43 | 634.76 | 36.6% | E71 | 591.83 | 22.1% | E43 | 864.32 | 19.6% | S84 | 359.22 | 20.7% | S41 | 480.88 | 18.0% | S41 | 480.88 | 10.9% |
| | Rodman | 6 | 0 | 166.46 | 0 | 998.76 | | E24 | 182.22 | 10.5% | E62 | 522.9 | 19.6% | E62 | 683.48 | 15.5% | S65 | 240.87 | 13.9% | S66 | 376.01 | 14.1% | S84 | 403.46 | 9.2% |
| | Laborer | 7 | 167.29 | 140.41 | 1171.03 | 982.87 | | E26 | 167.51 | 9.7% | E42 | 370.73 | 13.9% | E71 | 591.83 | 13.4% | S74 | 197.01 | 11.4% | S56 | 288.43 | 10.8% | S66 | 376.01 | 8.5% |
| | Equipment Operator | 1 | 40.85 | 32.49 | 40.85 | 32.49 | | | | | | | | | | | | | | | | | | | |
| | Total | 20 | | | 1732.38 | 2672.44 | | Representative | | 56.8% | | | 55.6% | Representative | | 48.6% | Representative | | 46.0% | | | 42.9% | Representative | | 28.6% |
| SOG | Carpenter | 4 | 86.75 | 109.72 | 347 | 438.88 | 4493.92 | E43 | 488.72 | 28.7% | E71 | 767.28 | 27.5% | E71 | 767.28 | 17.1% | S84 | 296.76 | 17.4% | S41 | 472.42 | 16.9% | S41 | 472.42 | 10.5% |
| | Rodman | 6 | 0 | 166.46 | 0 | 998.76 | | E24 | 213.92 | 12.6% | E62 | 491.64 | 17.6% | E43 | 686.88 | 15.3% | S65 | 192.3 | 11.3% | S56 | 335.94 | 12.0% | S56 | 335.94 | 7.5% |
| | Laborer | 6 | 167.29 | 140.41 | 1003.74 | 842.46 | | E62 | 145.56 | 8.5% | E42 | 331.88 | 11.9% | E62 | 637.2 | 14.2% | S32 | 173 | 10.2% | S66 | 334.6 | 12.0% | S84 | 335.88 | 7.5% |
| | Concrete Finisher | 12 | 22.54 | 37.16 | 270.48 | 445.92 | | | | | | | | | | | | | | | | | | | |
| | Equipment Operator | 2 | 40.85 | 32.49 | 81.7 | 64.98 | | | | | | | | | | | | | | | | | | | |
| | Total | 30 | | | 1702.92 | 2791 | | Representative | | 49.8% | | | 57.0% | Representative | | 46.5% | Representative | | 38.9% | | | 41.0% | Representative | | 25.5% |
| FRP Column | Carpenter | 2 | 86.75 | 109.72 | 173.5 | 219.44 | 2362.92 | E43 | 293.52 | 33.2% | E71 | 332.02 | 22.4% | E43 | 418.84 | 17.7% | S84 | 186.44 | 21.1% | S41 | 278.58 | 18.8% | S41 | 278.58 | 11.8% |
| | Rodman | 4 | 0 | 166.46 | 0 | 665.84 | | E26 | 102.1 | 11.6% | E62 | 269.46 | 18.2% | E62 | 359.68 | 15.2% | S65 | 119.94 | 13.6% | S66 | 211.8 | 14.3% | S84 | 212.17 | 9.0% |
| | Laborer | 4 | 167.29 | 140.41 | 669.16 | 561.64 | | E62 | 90.22 | 10.2% | E42 | 210.59 | 14.2% | E71 | 332.02 | 14.1% | S74 | 86.82 | 9.8% | S56 | 168.77 | 11.4% | S66 | 211.8 | 9.0% |
| | Equipment Operator | 1 | 40.85 | 32.49 | 40.85 | 32.49 | | | | | | | | | | | | | | | | | | | |
| | Total | 11 | | | 883.51 | 1479.41 | | Representative | | 55.0% | | | 54.9% | Representative | | 47.0% | Representative | | 44.5% | | | 44.6% | Representative | | 29.7% |
| Place Concrete | Carpenter | 3 | 86.75 | 109.72 | 260.25 | 329.16 | 6254.83 | E43 | 931.88 | 30.4% | E62 | 789.61 | 24.8% | E43 | 1214.66 | 19.4% | S84 | 657.81 | 21.4% | S41 | 386.41 | 12.1% | S84 | 757.58 | 12.1% |
| | Laborer | 16 | 167.29 | 140.41 | 2676.64 | 2676.64 | | E24 | 389.92 | 12.7% | E71 | 498.03 | 15.6% | E62 | 1093.62 | 17.5% | S65 | 417.81 | 13.6% | S56 | 267.86 | 8.4% | S65 | 538.51 | 8.6% |
| | Concrete Finisher | 4 | 22.54 | 37.16 | 90.16 | 148.64 | | E62 | 304.01 | 9.9% | E43 | 282.78 | 8.9% | E71 | 498.03 | 8.0% | S74 | 257.13 | 8.4% | S66 | 261.92 | 8.2% | S41 | 386.41 | 6.2% |
| | Equipment Operator | 1 | 40.85 | 32.49 | 40.85 | 32.49 | | | | | | | | | | | | | | | | | | | |
| | Total | 24 | | | 3067.9 | 3186.93 | | Representative | | 53.0% | | | 49.3% | Representative | | 44.9% | Representative | | 43.4% | | | 28.7% | Representative | | 26.9% |
| Form Deck | Carpenter | 16 | 86.75 | 109.72 | 1388 | 1755.52 | 4374.32 | E43 | 971.68 | 47.2% | E71 | 864.87 | 37.3% | E43 | 1174.62 | 26.9% | S84 | 386.64 | 18.8% | S41 | 311.84 | 13.5% | S65 | 482.48 | 11.0% |
| | Laborer | 4 | 167.29 | 140.41 | 669.16 | 561.64 | | E26 | 237.4 | 11.5% | E42 | 555.57 | 24.0% | E71 | 864.87 | 19.8% | S74 | 339.24 | 16.5% | S66 | 300.84 | 13.0% | S74 | 413.24 | 9.4% |
| | | | | | 2057.16 | 2317.16 | | E24 | 142.88 | 6.9% | E62 | 260.29 | 11.2% | E42 | 555.57 | 12.7% | S65 | 293.4 | 14.3% | S65 | 189.08 | 8.2% | S84 | 411.32 | 9.4% |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Total | 20 | | | | | | Representative | | 65.7% | | | 72.5% | Representative | | 59.3% | Representative | | 49.5% | | | 34.6% | Representative | | 29.9% |
| Rebar/MEP Slab | Rodman | 15 | 0 | 166.46 | 0 | 2496.9 | 3409.57 | E51 | 85.93 | 22.2% | E71 | 855.81 | 28.3% | E71 | 855.81 | 25.1% | S84 | 78.41 | 20.3% | S41 | 693.46 | 22.9% | S41 | 693.46 | 20.3% |
| | Electrician | 3 | 86.75 | 90.66 | 260.25 | 271.98 | | E26 | 74.81 | 19.3% | E42 | 515.96 | 17.1% | E42 | 515.96 | 15.1% | S44 | 61.47 | 15.9% | S66 | 526.19 | 17.4% | S66 | 526.19 | 15.4% |
| | Plumber | 2 | 63.33 | 126.89 | 126.66 | 253.78 | | E43 | 48.92 | 12.6% | E62 | 447.1 | 14.8% | E62 | 467.1 | 13.7% | S74 | 20.86 | 5.4% | S56 | 416.41 | 13.8% | S56 | 416.41 | 12.2% |
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Total | 20 | | | 386.91 | 3022.66 | | Representative | | 54.2% | | | 60.2% | Representative | | 53.9% | Representative | | 41.5% | | | 54.1% | Representative | | 48.0% |

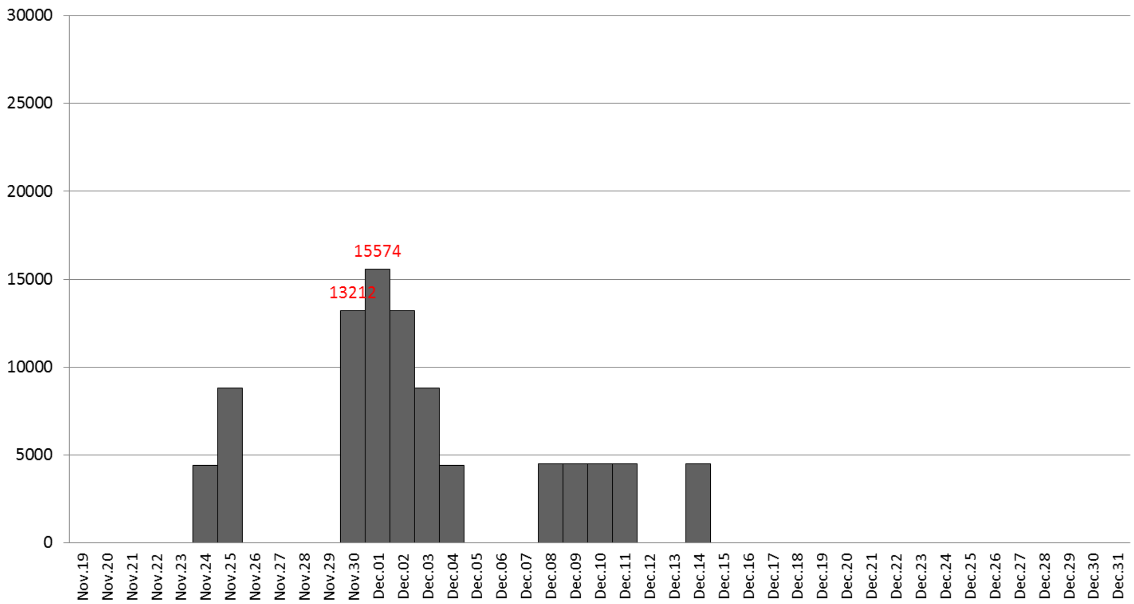
## I.3 Final Work Period Analysis

| Date | Safety Score | Activities | | Common Hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/8/2015 | 20067 | FRP Vertical Walls Level B3-W1 | 4404 | E43 | 3698.68 | 18.4% | S41 | 2193.64 | 10.9% |
| 12/9/2015 | | FRP Vertical Walls Level B3-W3 | 4404 | E62 | 3047.32 | 15.2% | S84 | 1758.43 | 8.8% |
| | | FRP Vertical Walls Level B3-W2 | 4404 | E71 | 2874.79 | 14.3% | S66 | 1674.43 | 8.3% |
| | | SOG Pour 1 | 4493 | | | | | | |
| | | FRP Columns Level B3 (in SOG2) | 2362 | | | 47.9% | | | 28.0% |
| 12/17/2015 | 20037 | FRP Vertical Walls Level B3-W6 | 4404 | E43 | 4013.08 | 20.0% | S41 | 2024.6 | 10.1% |
| 12/18/2015 | | FRP Vertical Walls Level B3-W5 | 4404 | E62 | 3092.32 | 15.4% | S84 | 1766.29 | 8.8% |
| | | SOG Pour 2 | 4493 | E71 | 2764.12 | 13.8% | S66 | 1599.26 | 8.0% |
| | | FRP Columns Level B3 (in SOG3) | 2362 | | | | | | |
| | | Form Deck Level B2 Pour 1 | 4374 | | | 49.3% | | | 26.9% |
| 12/21/2015 | 27850 | FRP Vertical Walls Level B3-W7 | 4404 | E43 | 5135.45 | 18.4% | S41 | 3198.94 | 11.5% |
| | | FRP Vertical Walls Level B3-W6 | 4404 | E62 | 4242.9 | 15.2% | S66 | 2501.46 | 9.0% |
| | | FRP Vertical Walls Level B3-S1 | 4404 | E71 | 4211.76 | 15.1% | S84 | 2261.12 | 8.1% |
| | | SOG Pour 2 | 4493 | | | | | | |
| | | FRP Columns Level B3 (in SOG3) | 2362 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 3409 | | | | | | |
| | | Form Deck Level B2 Pour 1 | 4374 | | | 48.8% | | | 28.6% |
| 12/23/2015 | 23476 | FRP Vertical Walls Level B3-W7 | 4404 | E43 | 3956.73 | 16.9% | S41 | 2887.1 | 12.3% |
| | | FRP Vertical Walls Level B3-S2 | 4404 | E71 | 3730.6 | 15.9% | S66 | 2200.62 | 9.4% |
| | | FRP Vertical Walls Level B3-S3 | 4404 | E62 | 3514.42 | 15.0% | S84 | 1849.8 | 7.9% |
| | | SOG Pour 3 | 4493 | | | | | | |
| | | FRP Columns Level B3 (in SOG4) | 2362 | | | | | | |
| | | Rebar/MEP Slab Rough Level B2 Pour1 | 3409 | | | 47.7% | | | 29.6% |
| 12/28/2015 | 21917 | FRP Vertical Walls Level B3-S2 | 4404 | E43 | 3984.02 | 18.2% | S41 | 2078.61 | 9.5% |
| | | FRP Vertical Walls Level B3-S4 | 4404 | E62 | 3397.02 | 15.5% | S84 | 2068.32 | 9.4% |
| | | SOG Pour 3 | 4493 | E71 | 2759.78 | 12.6% | S65 | 1624.83 | 7.4% |
| | | FRP Columns Level B3 (in SOG4) | 2362 | | | | | | |
| | | Place Concrete Level B2 Pour 1 | 6254 | | | 46.3% | | | 26.3% |

## I.4 Final Work Zone Analysis

### I.4.1 Basement 3_Zone 1

- Safety score profile for B3_Zone1

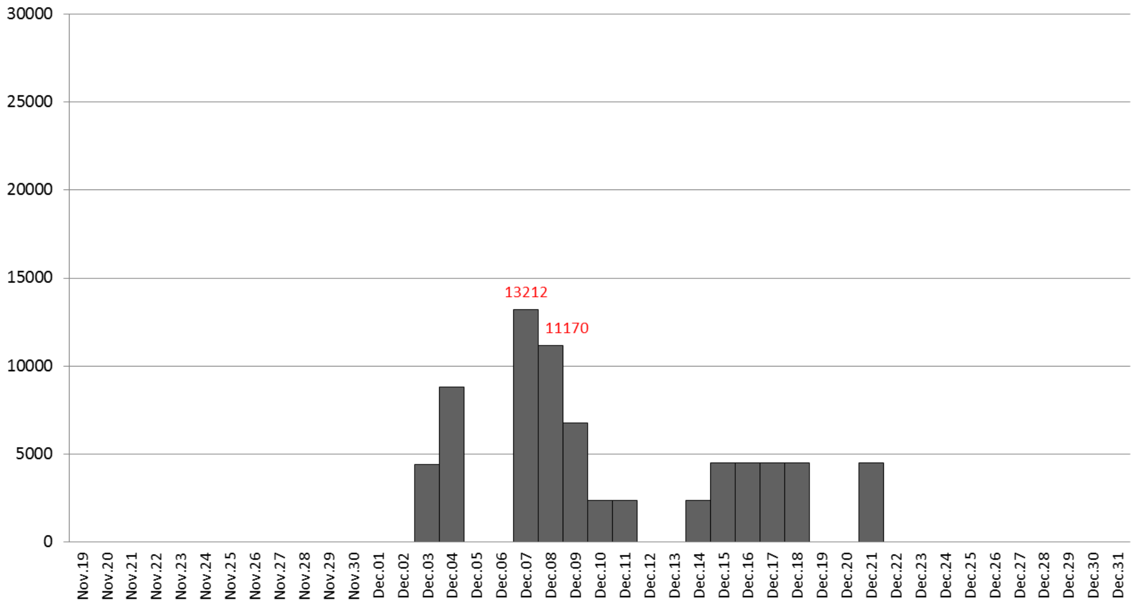



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/1/2015 | 15574 | FRP Vertical Walls Level B3-E1 | 4404 | E43 | 3011.8 | 19.3% | S41 | 1721.22 | 11.1% |
| | | FRP Vertical Walls Level B3-N4 | 4404 | E62 | 2410.12 | 15.5% | S84 | 1422.55 | 9.1% |
| | | FRP Vertical Walls Level B3-N3 | 4404 | E71 | 2107.51 | 13.5% | S66 | 1339.83 | 8.6% |
| | | FRP Columns Level B3 (in SOG1) | 2362 | | | | | | |
| | | | | | | 48.3% | | | 28.8% |
| 11/30/2015 | 13212 | FRP Vertical Walls Level B3-E1 | 4404 | E43 | 2592.96 | 19.6% | S41 | 1442.64 | 10.9% |
| | | FRP Vertical Walls Level B3-N4 | 4404 | E62 | 2050.44 | 15.5% | S84 | 1210.38 | 9.2% |
| | | FRP Vertical Walls Level B3-EW1 | 4404 | E71 | 1775.49 | 13.4% | S66 | 1128.03 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |

### I.4.2 Basement 3_Zone 2

- Safety score profile for B3_Zone2

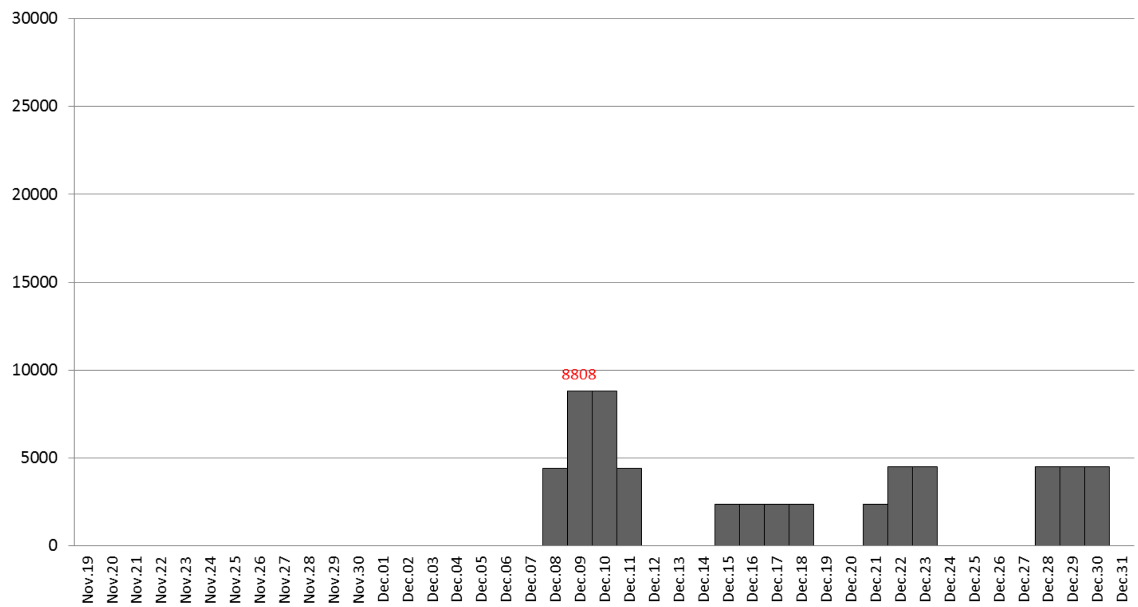



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/7/2015 | 13212 | FRP Vertical Walls Level B3-W1 | 4404 | E43 | 2592.96 | 16.6% | S41 | 1442.64 | 10.9% |
| | | FRP Vertical Walls Level B3-N1 | 4404 | E62 | 2050.44 | 13.2% | S84 | 1210.38 | 9.2% |
| | | FRP Vertical Walls Level B3-W2 | 4404 | E71 | 1775.49 | 11.4% | S66 | 1128.03 | 8.5% |
| | | | | | | | | | |
| | | | | | | 41.2% | | | 28.6% |
| 12/8/2015 | 11170 | FRP Vertical Walls Level B3-W1 | 4404 | E43 | 2147.48 | 19.2% | S41 | 1240.34 | 11.1% |
| | | FRP Vertical Walls Level B3-W2 | 4404 | E62 | 1726.64 | 15.5% | S66 | 963.82 | 8.6% |
| | | FRP Columns Level B3 (in SOG2) | 2362 | E71 | 1515.68 | 13.6% | S84 | 1019.09 | 9.1% |
| | | | | | | | | | |
| | | | | | | 48.3% | | | 28.9% |

### I.4.3 Basement 3_Zone 3

- Safety score profile for B3_Zone3

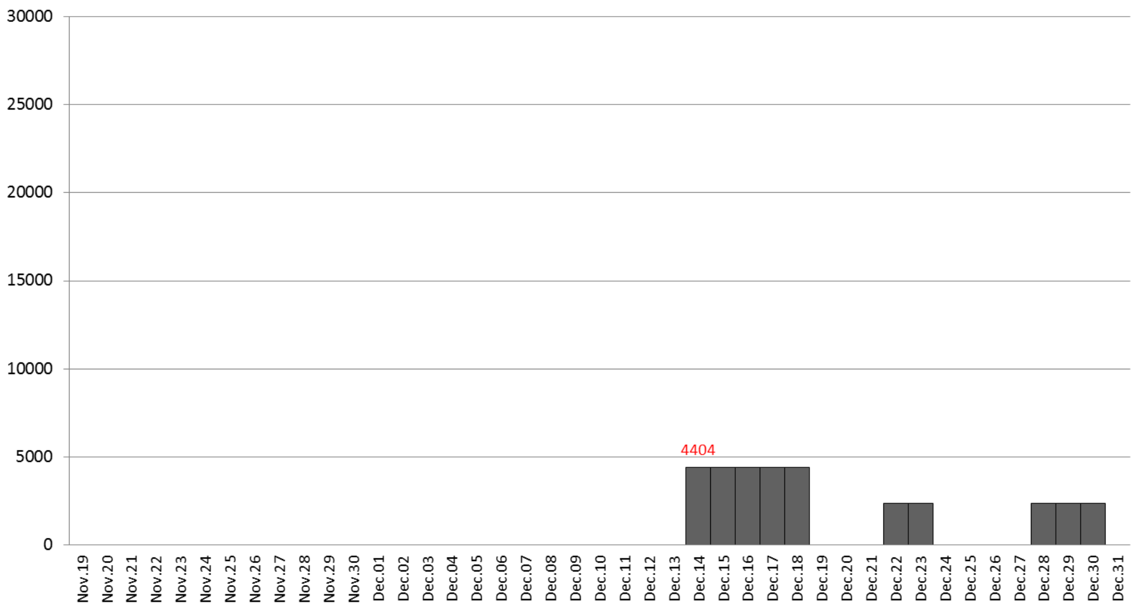



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/9/2015 | 8808 | FRP Vertical Walls Level B3-W4 | 4404 | E43 | 1728.64 | 19.6% | S41 | 961.76 | 10.9% |
| | | FRP Vertical Walls Level B3-W3 | 4404 | E62 | 1366.96 | 15.5% | S84 | 806.92 | 9.2% |
| | | | | E71 | 1183.66 | 13.4% | S66 | 752.02 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |
| 12/10/2015 | 8808 | FRP Vertical Walls Level B3-W4 | 4404 | E43 | 1728.64 | 19.6% | S41 | 961.76 | 10.9% |
| | | FRP Vertical Walls Level B3-W3 | 4404 | E62 | 1366.96 | 15.5% | S84 | 806.92 | 9.2% |
| | | | | E71 | 1183.66 | 13.4% | S66 | 752.02 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |

## I.4.4 Basement 3_Zone 4

- Safety score profile for B3_Zone4

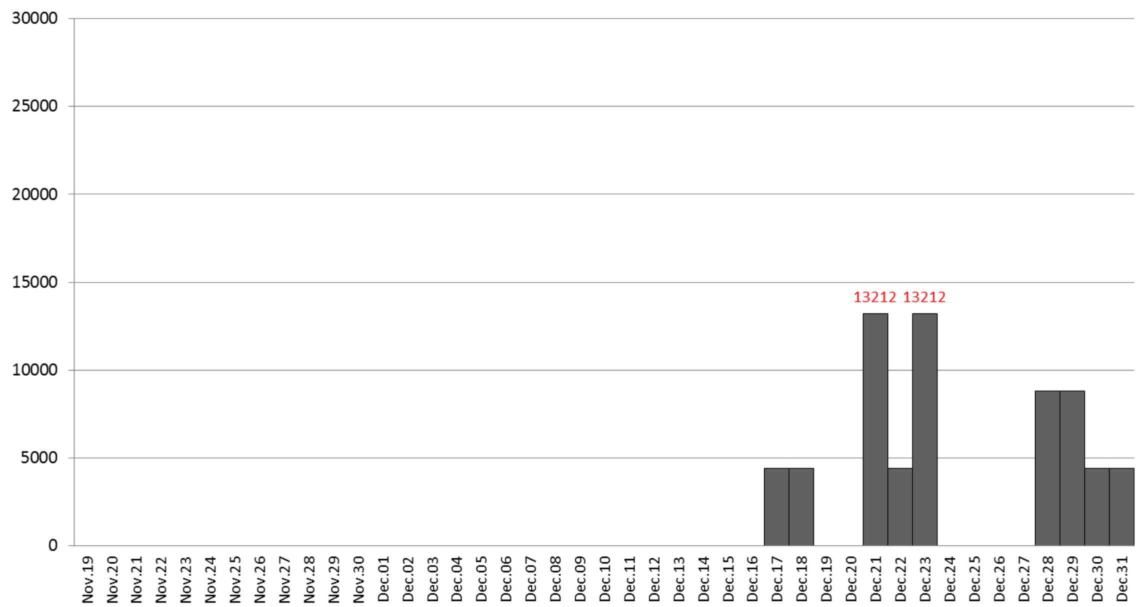



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/14/2015 | 4404 | FRP Vertical Walls Level B3-W5 | 4404 | E43 | 864.32 | 19.6% | S41 | 480.88 | 10.9% |
| - | | | | E62 | 683.48 | 15.5% | S84 | 403.46 | 9.2% |
| 12/18/2015 | | | | E71 | 591.83 | 13.4% | S66 | 376.01 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |
| | | | | | | | | | |

### I.4.5 Basement 3_Zone 5

- Safety score profile for B3_Zone5

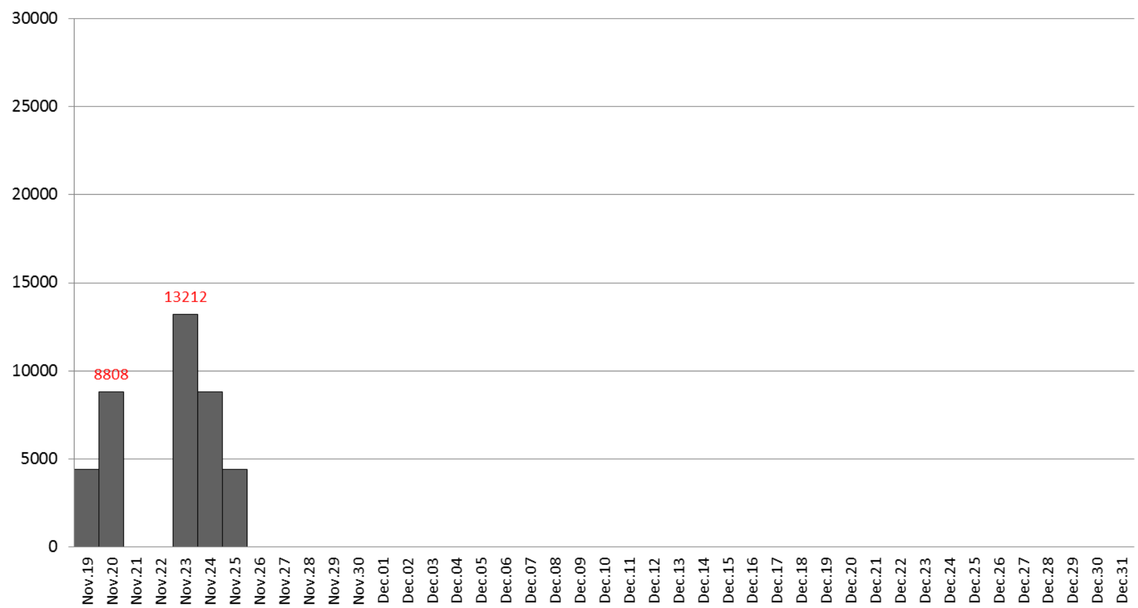



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 13212 | FRP Vertical Walls Level B3-W7 | 4404 | E43 | 2592.96 | 19.6% | S41 | 1442.64 | 10.9% |
| | | FRP Vertical Walls Level B3-W6 | 4404 | E62 | 2050.44 | 15.5% | S84 | 1210.38 | 9.2% |
| | | FRP Vertical Walls Level B3-S1 | 4404 | E71 | 1775.49 | 13.4% | S66 | 1128.03 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |
| 11/23/2015 | 13212 | FRP Vertical Walls Level B3-W7 | 4404 | E43 | 2592.96 | 19.6% | S41 | 1442.64 | 10.9% |
| | | FRP Vertical Walls Level B3-S2 | 4404 | E62 | 2050.44 | 15.5% | S84 | 1210.38 | 9.2% |
| | | FRP Vertical Walls Level B3-S3 | 4404 | E71 | 1775.49 | 13.4% | S66 | 1128.03 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |

## I.4.6 Basement 3_Zone 6

- Safety score profile for B3_Zone6

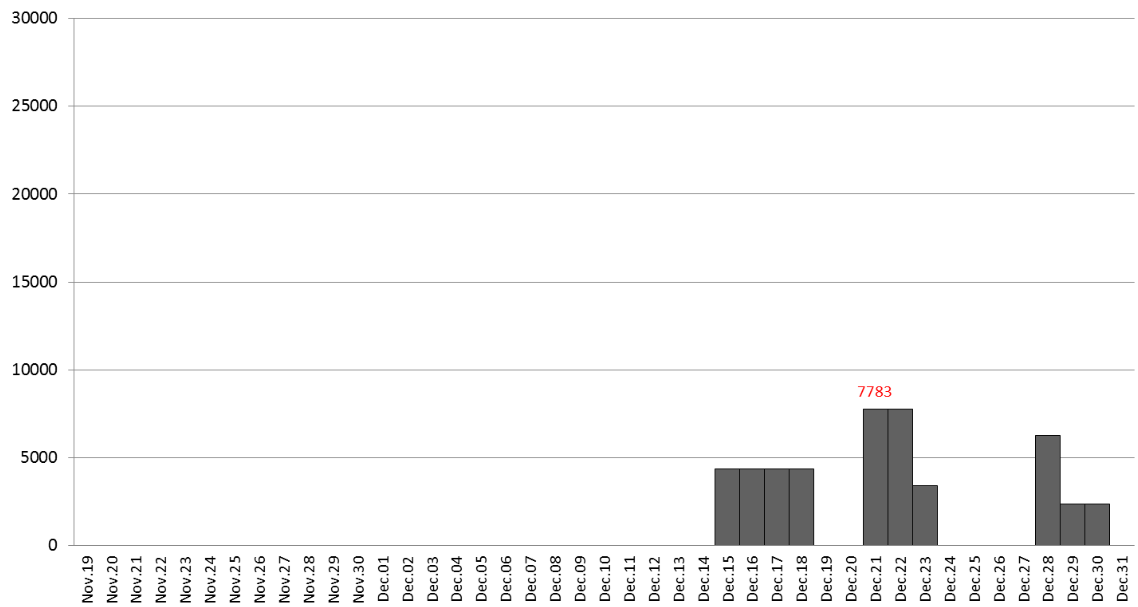



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 11/20/2015 | 8808 | FRP Vertical Walls Level B3-E4 | 4404 | E43 | 1728.64 | 19.6% | S41 | 961.76 | 10.9% |
| | | FRP Vertical Walls Level B3-E3 | 4404 | E62 | 1366.96 | 15.5% | S84 | 806.92 | 9.2% |
| | | | | E71 | 1183.66 | 13.4% | S66 | 752.02 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |
| 11/23/2015 | 13212 | FRP Vertical Walls Level B3-E2 | 4404 | E43 | 2592.96 | 19.6% | S41 | 1442.64 | 10.9% |
| | | FRP Vertical Walls Level B3-E4 | 4404 | E62 | 2050.44 | 15.5% | S84 | 1210.38 | 9.2% |
| | | FRP Vertical Walls Level B3-E3 | 4404 | E71 | 1775.49 | 13.4% | S66 | 1128.03 | 8.5% |
| | | | | | | | | | |
| | | | | | | 48.6% | | | 28.6% |

### I.4.7 Basement 2_Zone 1

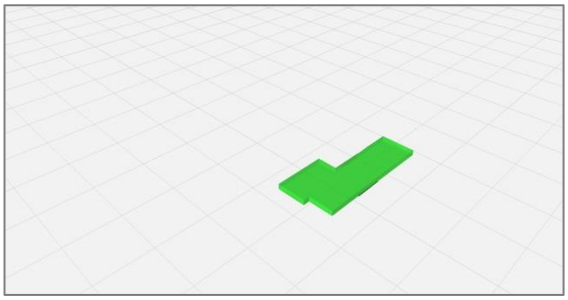
- Safety score profile for B2_Zone1

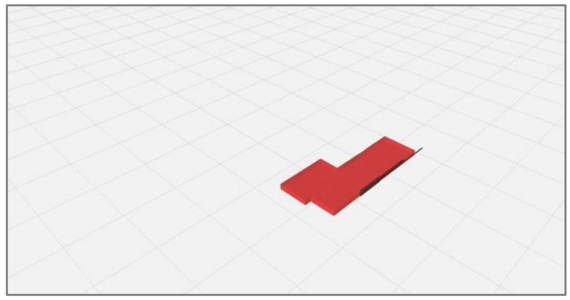


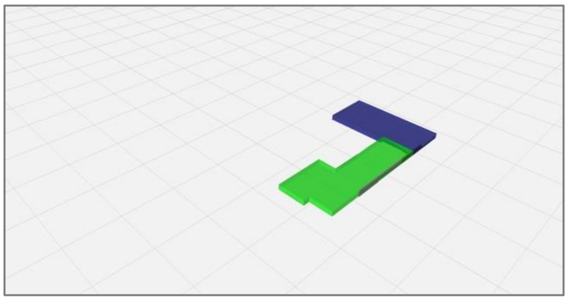

- Safety analysis for selected dates

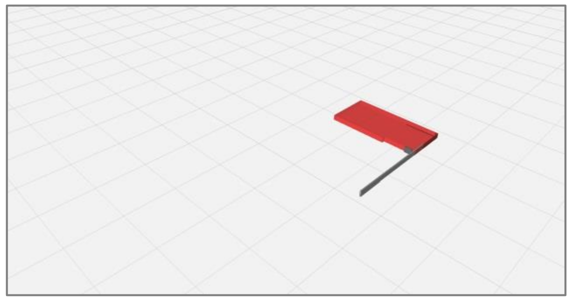
| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 12/21/2015 | 7783 | Rebar/MEP Slab Rough Level B2 Po | 3409 | E43 | 1436.77 | 18.5% | S41 | 1005.3 | 12.9% |
| | | Form Deck Level B2 Pour 1 | 4374 | E62 | 1195.58 | 15.4% | S66 | 827.03 | 10.6% |
| | | | | E71 | 1336.97 | 17.2% | S56 | 591.53 | 7.6% |
| | | | | | | | | | |
| | | | | | | 51.0% | | | 31.1% |
| 12/22/2015 | 7783 | Rebar/MEP Slab Rough Level B2 Po | 3409 | E43 | 1436.77 | 18.5% | S41 | 1005.3 | 12.9% |
| | | Form Deck Level B2 Pour 1 | 4374 | E62 | 1195.58 | 15.4% | S66 | 827.03 | 10.6% |
| | | | | E71 | 1336.97 | 17.2% | S56 | 591.53 | 7.6% |
| | | | | | | | | | |
| | | | | | | 51.0% | | | 31.1% |

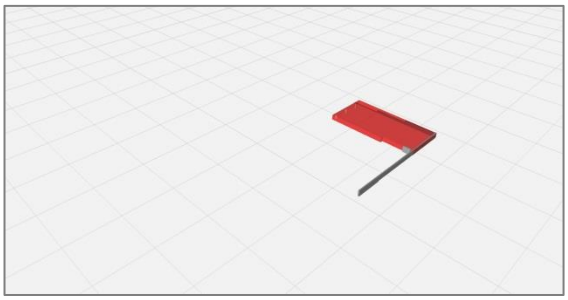
## I.5 SCREEN SHOTS OF SAFETY 4D SIMULATION

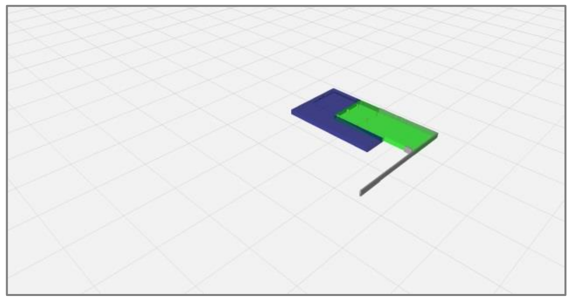

11/19/2015

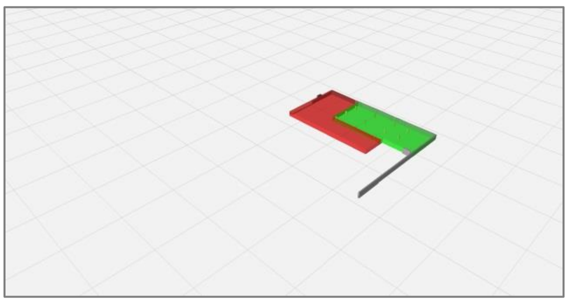

11/23/2015

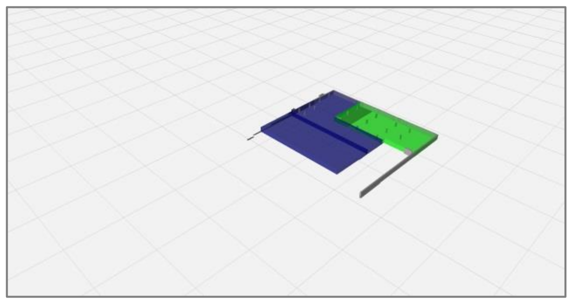

11/25/2015

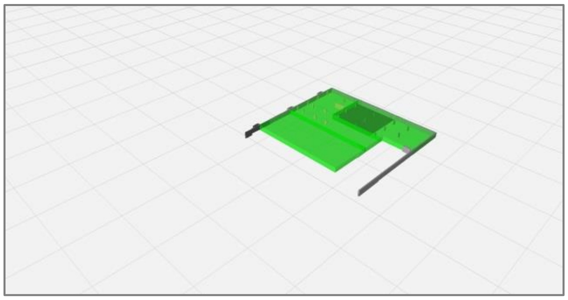

11/30/2015


12/02/2015

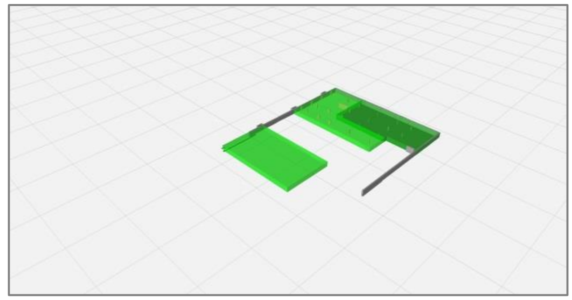

12/04/2015


12/07/2015

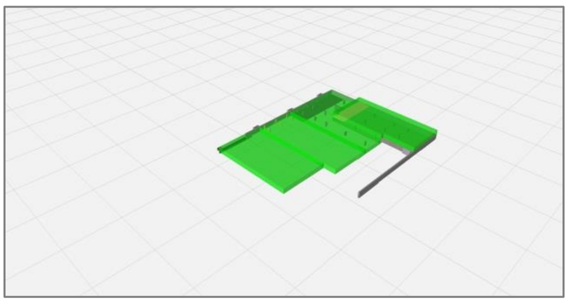

12/09/2015



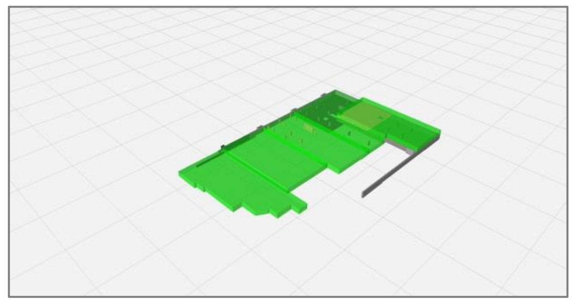
12/112015



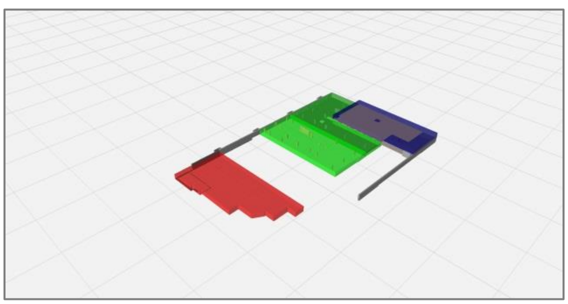
12/14/2015



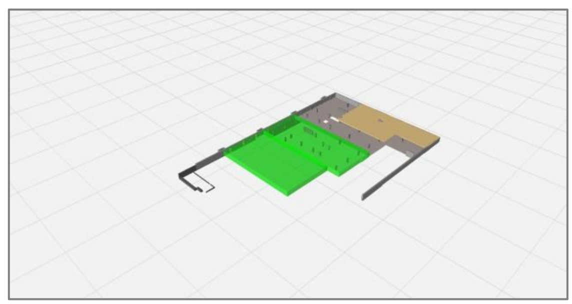
12/16/2015



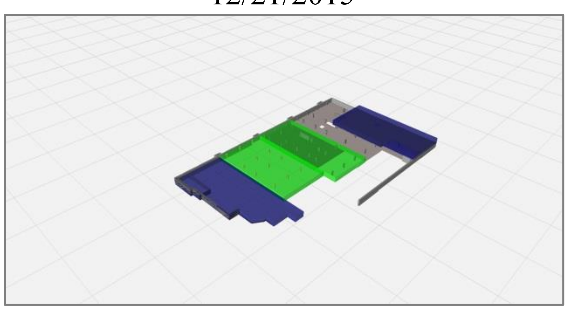
12/18/2015



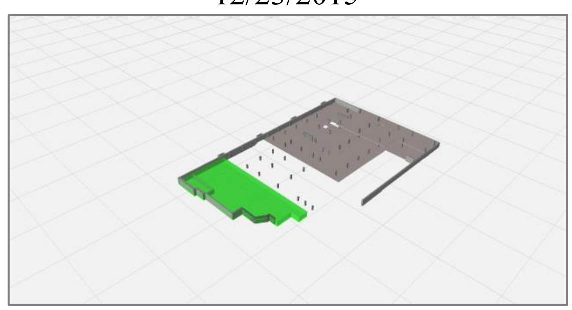
12/21/2015



12/23/2015



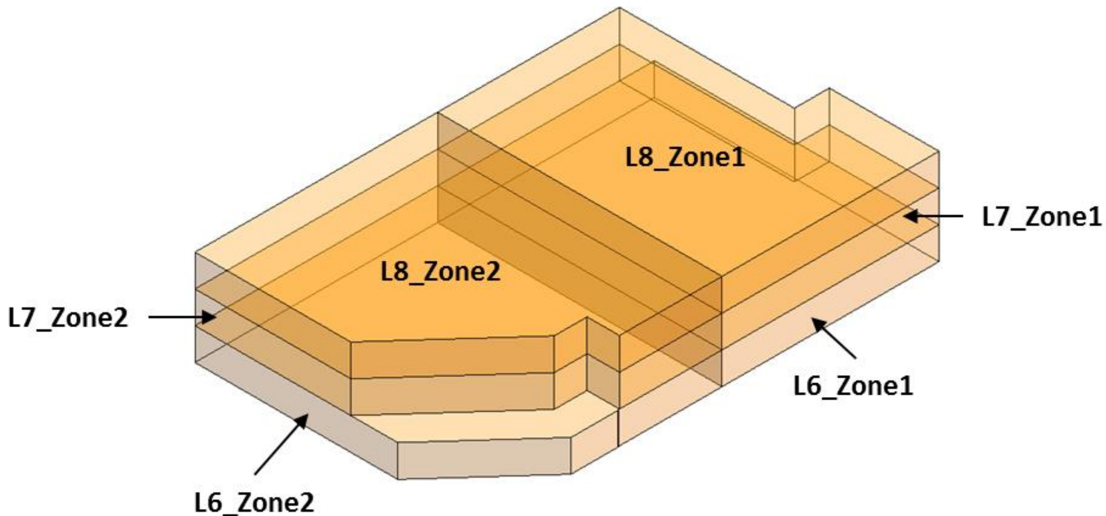
12/28/2015



12/31/2015

# Appendix J – Final Safety Analysis of Project B (Office Building)

## J.1 Zoning Plan



## J.2 Final Activity Analysis

| Type | Occupation | Number of workers | Individual | | Total | | Activity Safety Score |
|---|---|---|---|---|---|---|---|
| | | | Fatality | Days away | Fatality | Days away | |
| Form Deck | Carpenter | 21 | 86.75 | 109.72 | 1821.75 | 2304.12 | 6895.17 |
| | Laborer | 9 | 167.29 | 140.41 | 1505.61 | 1263.69 | |
| | | | | | | | |
| | | | | | | | |
| | Total | 30 | | | 3327.36 | 3567.81 | |
| FRP Vertical Concrete Column | Carpenter | 2 | 86.75 | 109.72 | 173.5 | 219.44 | 2030 |
| | Rodman | 2 | 0 | 166.46 | 0 | 332.92 | |
| | Laborer | 4 | 167.29 | 140.41 | 669.16 | 561.64 | |
| | Equipment Operator | 1 | 40.85 | 32.49 | 40.85 | 32.49 | |
| | Total | 9 | | | 883.51 | 1146.49 | |
| Rebar/MEP Slab | Rodman | 15 | 0 | 166.46 | 0 | 2496.9 | 3409.57 |
| | Electrician | 3 | 86.75 | 90.66 | 260.25 | 271.98 | |
| | Plumber | 2 | 63.33 | 126.89 | 126.66 | 253.78 | |
| | | | | | | | |
| | Total | 20 | | | 386.91 | 3022.66 | |
| Place Concrete | Carpenter | 4 | 86.75 | 109.72 | 347 | 438.88 | 2818.16 |
| | Laborer | 3 | 167.29 | 140.41 | 501.87 | 501.87 | |
| | Concrete Finisher | 16 | 22.54 | 37.16 | 360.64 | 594.56 | |
| | Equipment Operator | 1 | 40.85 | 32.49 | 40.85 | 32.49 | |
| | Total | 24 | | | 1250.36 | 1567.8 | |

| Type | Occupation | Common Hazard Types | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Fatality | | | Days Away Injury | | | Total | | |
| | | Type | Amoun | % | Type | Amoun | % | Type | Amount | % |
| Form Deck | Carpenter | E43 | 1459.68 | 43.9% | E62 | 931.11 | 26.1% | E43 | 1790.82 | 26.0% |
| | Laborer | E26 | 365.1 | 11.0% | E71 | 711.06 | 19.9% | E62 | 1182.78 | 17.2% |
| | | E24 | 270.78 | 8.1% | E42 | 422.31 | 11.8% | E71 | 711.06 | 10.3% |
| | | | | | | | | | | |
| | Total | Representative | | 63.0% | | | 57.9% | Representative | | 53.4% |
| FRP Vertical Concrete Column | Carpenter | E43 | 293.52 | 33.2% | E62 | 248.66 | 21.7% | E43 | 398.04 | 19.6% |
| | Rodman | E24 | 102.1 | 11.6% | E71 | 234.92 | 20.5% | E62 | 338.88 | 16.7% |
| | Laborer | E62 | 90.22 | 10.2% | E42 | 148.17 | 12.9% | E71 | 234.92 | 11.6% |
| | Equipment Operator | | | | | | | | | |
| | Total | Representative | | 55.0% | | | 55.1% | Representative | | 47.9% |
| Rebar/MEP Slab | Rodman | E51 | 85.93 | 22.2% | E71 | 855.81 | 28.3% | E71 | 855.81 | 25.1% |
| | Electrician | E26 | 74.81 | 19.3% | E42 | 515.96 | 17.1% | E42 | 515.96 | 15.1% |
| | Plumber | E43 | 48.92 | 12.6% | E62 | 447.1 | 14.8% | E62 | 467.1 | 13.7% |
| | | | | | | | | | | |
| | Total | Representative | | 54.2% | | | 60.2% | Representative | | 53.9% |
| Place Concrete | Carpenter | E43 | 341.24 | 27.3% | E71 | 489.83 | 31.2% | E71 | 489.83 | 17.4% |
| | Laborer | E24 | 158.82 | 12.7% | E62 | 316.04 | 20.2% | E43 | 427.08 | 15.2% |
| | Concrete Finisher | E26 | 87.89 | 7.0% | E42 | 101.01 | 6.4% | E62 | 397.84 | 14.1% |
| | Equipment Operator | | | | | | | | | |
| | Total | Representative | | 47.0% | | | 57.8% | Representative | | 46.7% |

| Type | Occupation | Common Sources of Injuires | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Fatality | | | Days Away Injury | | | Total | | |
| | | Type | Amount | % | Type | Amount | % | Type | Amount | % |
| Form Deck | Carpenter | S84 | 650.19 | 19.5% | S41 | 486.39 | 13.6% | S65 | 743.43 | 10.8% |
| | Laborer | S74 | 492.84 | 14.8% | S66 | 444.69 | 12.5% | S84 | 705.72 | 10.2% |
| | | S65 | 474.3 | 14.3% | S56 | 281.07 | 7.9% | S74 | 612.84 | 8.9% |
| | | | | | | | | | | |
| | Total | Representative | | 48.6% | | | 34.0% | Representative | | 29.9% |
| FRP Vertical Concrete Column | Carpenter | S84 | 186.44 | 21.1% | S41 | 195.36 | 17.0% | S84 | 212.17 | 10.5% |
| | Rodman | S66 | 149.38 | 16.9% | S66 | 149.38 | 13.0% | S41 | 195.36 | 9.6% |
| | Laborer | S74 | 86.82 | 9.8% | S56 | 120.21 | 10.5% | S65 | 163.14 | 8.0% |
| | Equipment Operator | | | | | | | | | |
| | Total | Representative | | 47.8% | | | 40.6% | Representative | | 28.1% |
| Rebar/MEP Slab | Rodman | S84 | 78.41 | 20.3% | S41 | 693.46 | 22.9% | S41 | 693.46 | 20.3% |
| | Electrician | S44 | 61.47 | 15.9% | S66 | 526.19 | 17.4% | S66 | 526.19 | 15.4% |
| | Plumber | S74 | 20.86 | 5.4% | S56 | 416.41 | 13.8% | S56 | 416.41 | 12.2% |
| | | | | | | | | | | |
| | Total | Representative | | 41.5% | | | 54.1% | Representative | | 48.0% |
| Place Concrete | Carpenter | S84 | 177.68 | 14.2% | S41 | 173.08 | 11.0% | S32 | 209.38 | 7.4% |
| | Laborer | S32 | 131.6 | 10.5% | S56 | 172.09 | 11.0% | S84 | 197.24 | 7.0% |
| | Concrete Finisher | S65 | 120.93 | 9.7% | S71 | 164.08 | 10.5% | S65 | 179.38 | 6.4% |
| | Equipment Operator | | | | | | | | | |
| | Total | Representative | | 34.4% | | | 32.5% | Representative | | 20.8% |

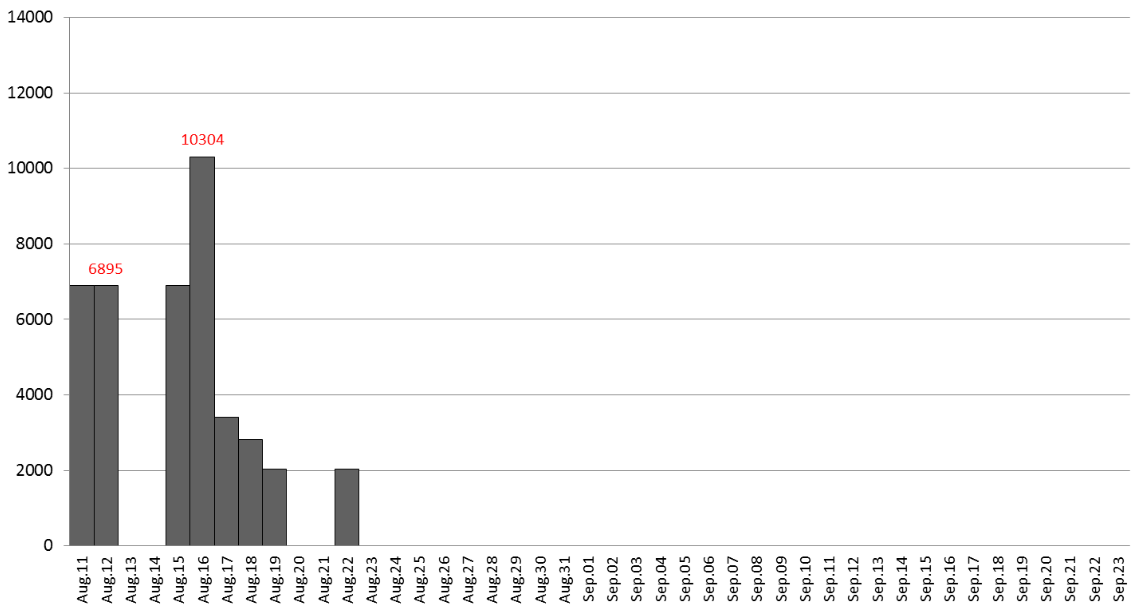
## J.3 Final Work Period Analysis

| Date | Safety Score | Activities | | Common hazard Types | | | Common Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/22/2016 | 12334 | FRP Vertical Concrete Level 6 Pour 1 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 6 Pour 2 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 6 Pour 2 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |
| 8/29/2016 | 12334 | FRP Vertical Concrete Level 6 Pour 2 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 7 Pour 1 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 7 Pour 1 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |
| 9/2/2016 | 12334 | FRP Vertical Concrete Level 6 Pour 2 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 7 Pour 1 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 7 Pour 1 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |
| 9/12/2016 | 12334 | FRP Vertical Concrete Level 7 Pour 1 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 7 Pour 2 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 7 Pour 2 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |
| 9/16/2016 | 12334 | FRP Vertical Concrete Level 7 Pour 2 | 2030 | E43 | 2446.91 | 19.8% | S41 | 1375.21 | 11.1% |
| | | Rebar/MEP Slab Rough Level 8 Pour 1 | 3409 | E62 | 1988.76 | 16.1% | S66 | 1120.26 | 9.1% |
| | | Form Deck Level 8 Pour 1 | 6895 | E71 | 1801.79 | 14.6% | S84 | 1009.26 | 8.2% |
| | | | | | | | | | |
| | | | | | | 50.6% | | | 28.4% |

## J.4 Final Work Zone Analysis

### J.4.1 Level 6_Zone 1

- Safety score profile for L6_Zone1

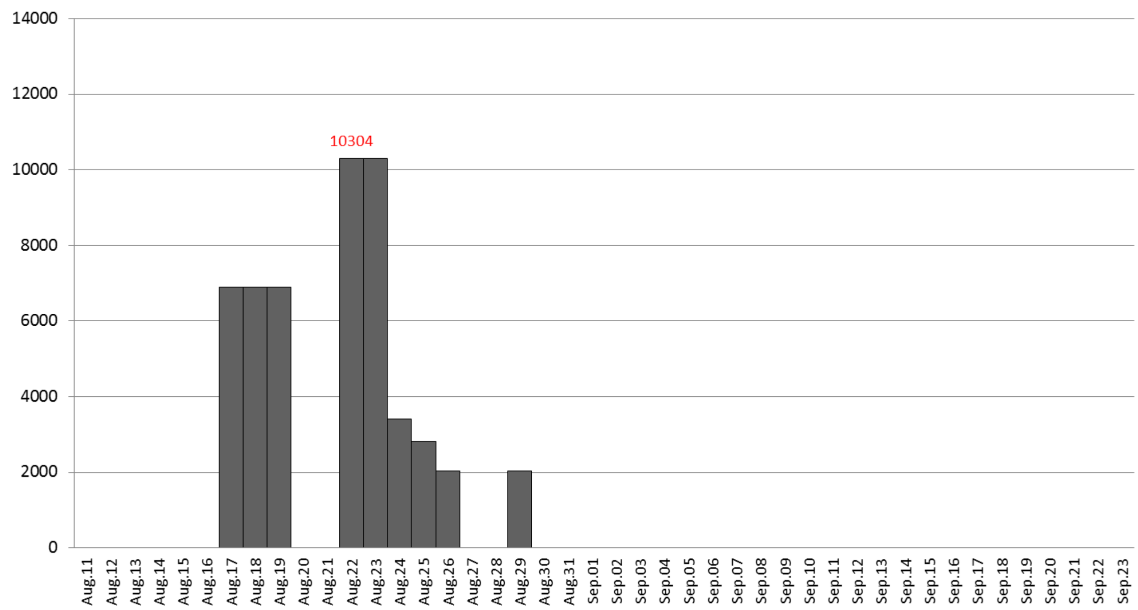



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/12/2016 | 6895 | Form Deck Level 6 Pour 1 | 6895 | E43 | 1790.82 | 26.0% | S65 | 743.43 | 10.8% |
| | | | | E62 | 1182.78 | 17.2% | S84 | 705.72 | 10.2% |
| | | | | E71 | 711.06 | 10.3% | S74 | 612.84 | 8.9% |
| | | | | | | | | | |
| | | | | | | 53.4% | | | 29.9% |
| 8/16/2016 | 10304 | Rebar/MEP Slab Rough Level 6 Pour 1 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 6 Pour 1 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.4.2 Level 6_Zone 2

- Safety score profile for L6_Zone2

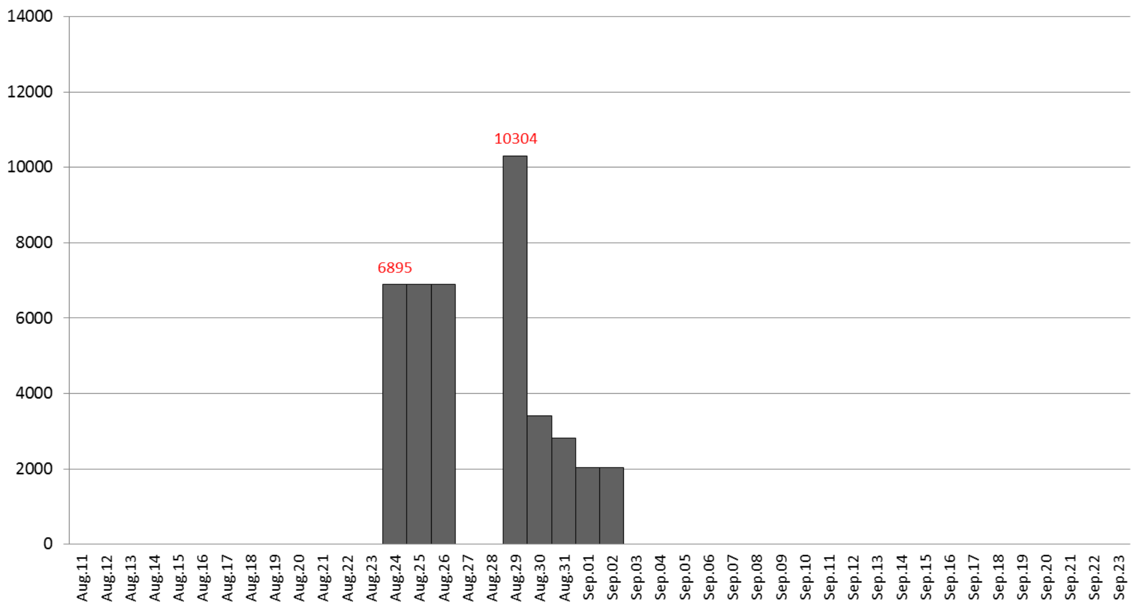



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/22/2016 | 10304 | Rebar/MEP Slab Rough Level 6 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 6 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |
| 8/23/2016 | 10304 | Rebar/MEP Slab Rough Level 6 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 6 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.4.3 Level 7_Zone 1

- Safety score profile for L7_Zone1

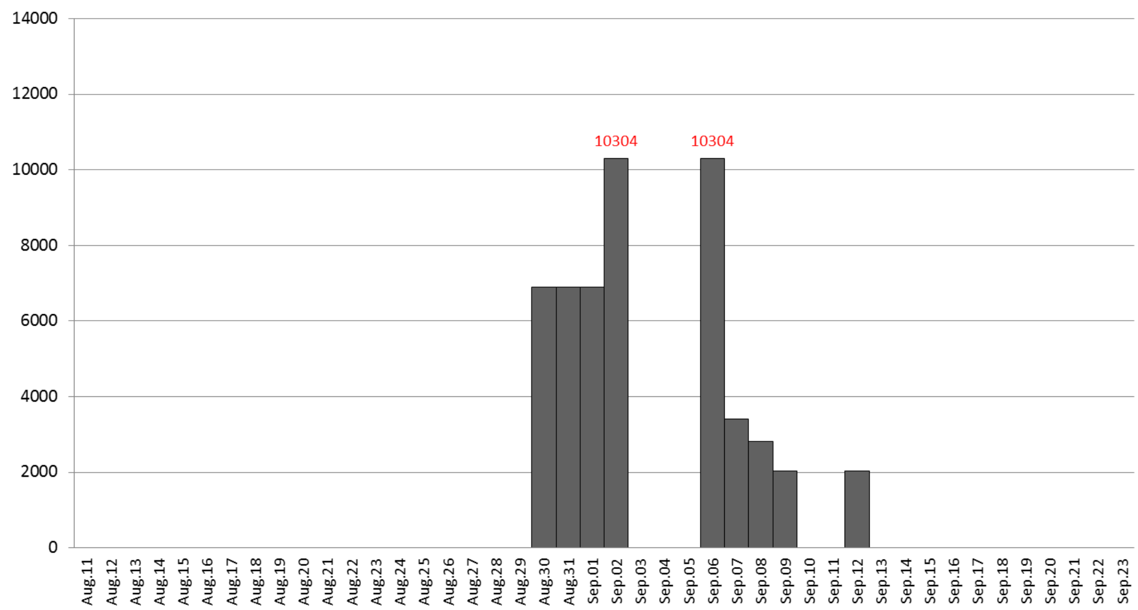



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 8/24/2016 | 6895 | Form Deck Level 7 Pour 1 | 6895 | E43 | 1790.82 | 26.0% | S65 | 743.43 | 10.8% |
| | | | | E62 | 1182.78 | 17.2% | S84 | 705.72 | 10.2% |
| | | | | E71 | 711.06 | 10.3% | S74 | 612.84 | 8.9% |
| | | | | | | | | | |
| | | | | | | 53.4% | | | 29.9% |
| 8/29/2016 | 10304 | Rebar/MEP Slab Rough Level 7 Pour 1 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 7 Pour 1 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.4.4 Level 7_Zone 2

- Safety score profile for L7_Zone2

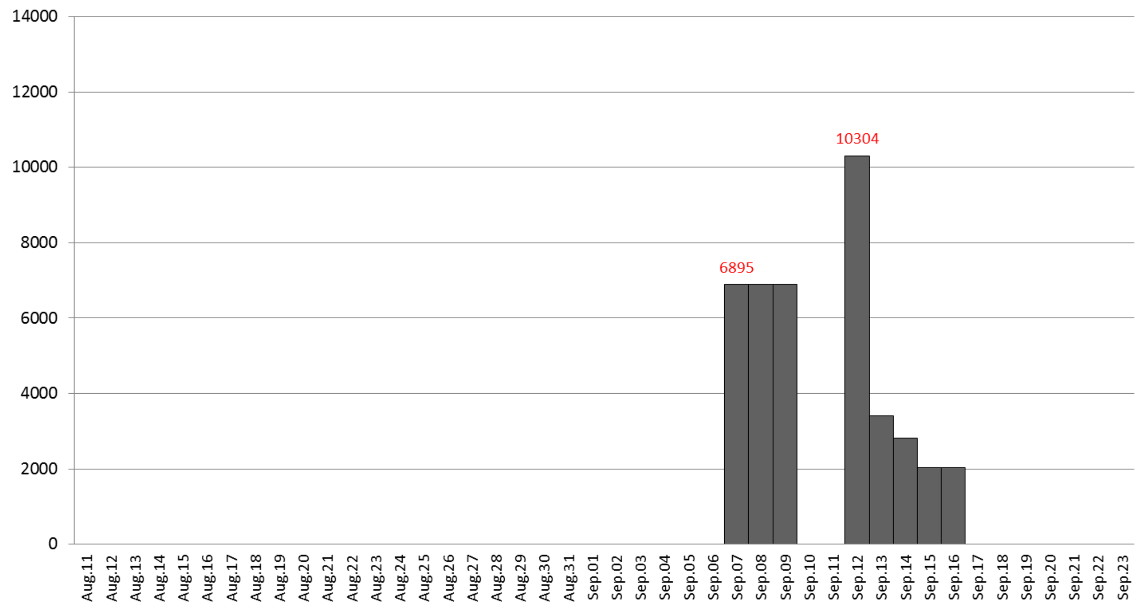



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 9/2/2016 | 10304 | Rebar/MEP Slab Rough Level 7 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 7 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |
| 9/6/2016 | 10304 | Rebar/MEP Slab Rough Level 7 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 7 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.4.5 Level 8_Zone 1

- Safety score profile for L8_Zone1

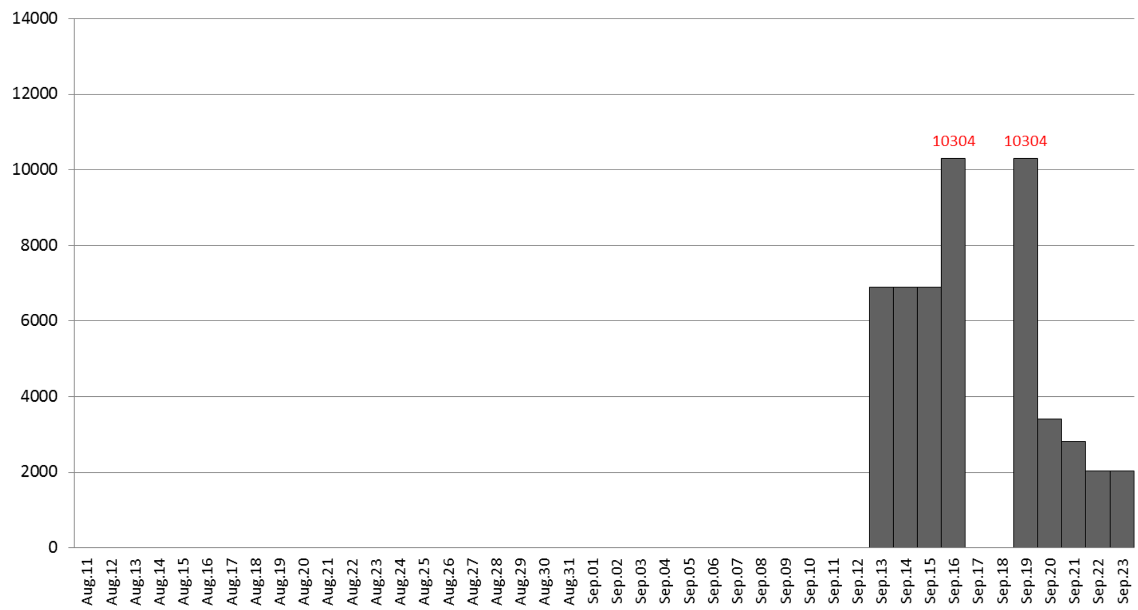



- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 9/7/2016 | 6895 | Form Deck Level 8 Pour 1 | 6895 | E43 | 1790.82 | 26.0% | S65 | 743.43 | 10.8% |
| | | | | E62 | 1182.78 | 17.2% | S84 | 705.72 | 10.2% |
| | | | | E71 | 711.06 | 10.3% | S74 | 612.84 | 8.9% |
| | | | | | | | | | |
| | | | | | | 53.4% | | | 29.9% |
| 9/12/2016 | 10304 | Rebar/MEP Slab Rough Level 8 Pour 1 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 8 Pour 1 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.4.6 Level 8_Zone 2

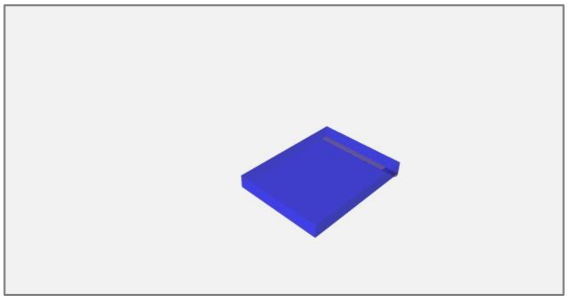
- Safety score profile for L8_Zone2




- Safety analysis for selected dates

| Date | Safety Score | Concurrent Activities | | Hazard Types | | | Sources of Injuries | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Type | Amount | % | Type | Amount | % |
| 9/16/2016 | 10304 | Form Deck Level 8 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Rebar/MEP Slab Rough Level 8 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |
| 9/19/2016 | 10304 | Rebar/MEP Slab Rough Level 7 Pour 2 | 6895 | E43 | 2048.87 | 19.9% | S41 | 1179.85 | 11.5% |
| | | Form Deck Level 8 Pour 2 | 3409 | E62 | 1649.88 | 16.0% | S66 | 970.88 | 9.4% |
| | | | | E71 | 1566.87 | 15.2% | S65 | 797.45 | 7.7% |
| | | | | | | | | | |
| | | | | | | 51.1% | | | 28.6% |

### J.5 Screen Shots of Safety 4D Simulation



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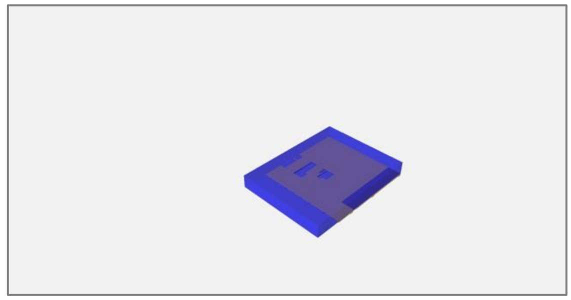

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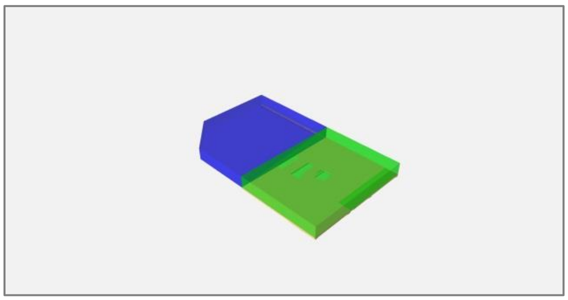

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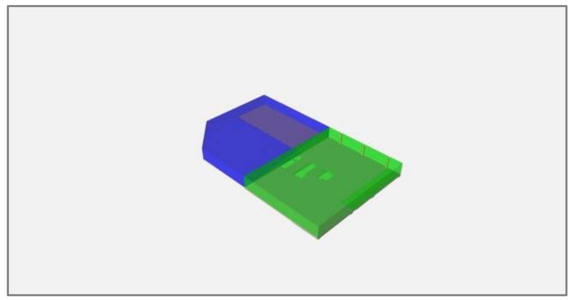

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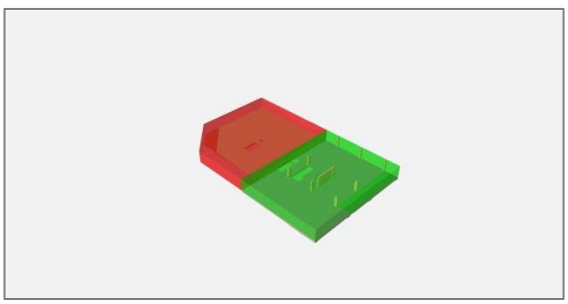

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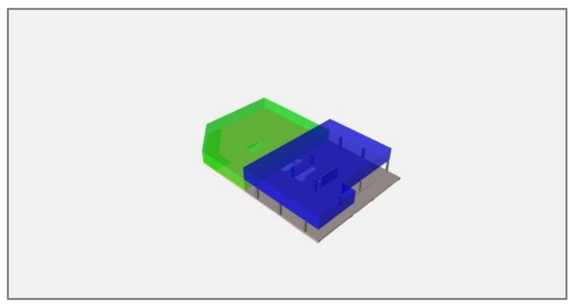

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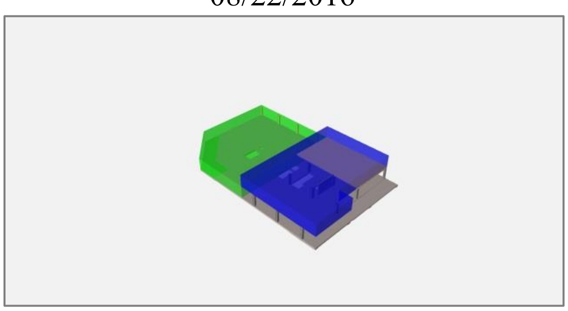

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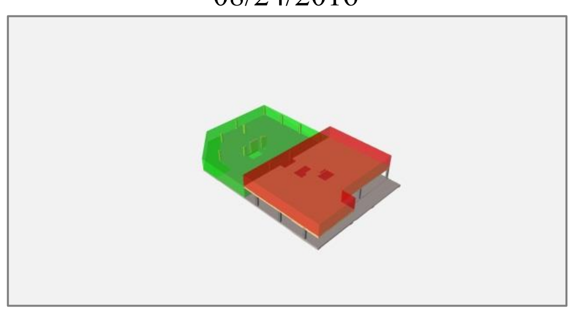

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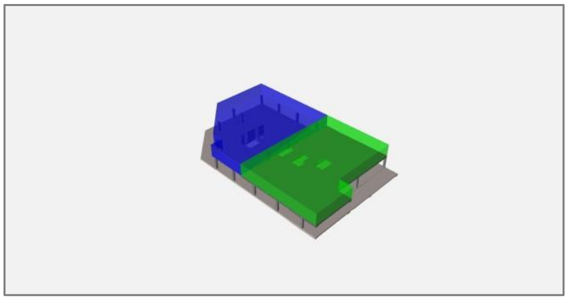
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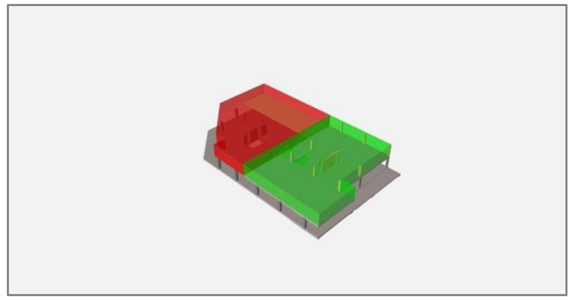
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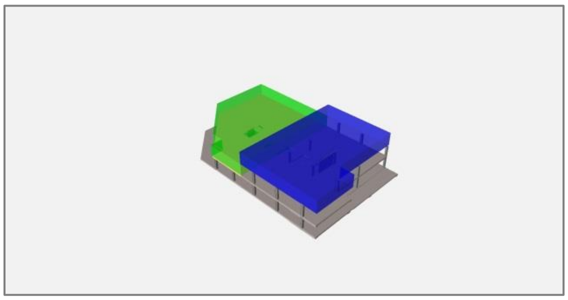
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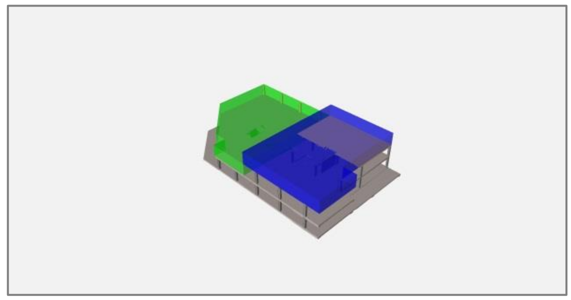
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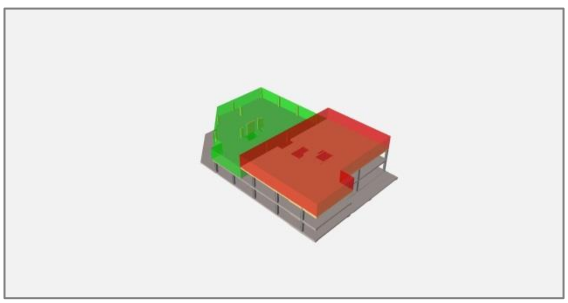
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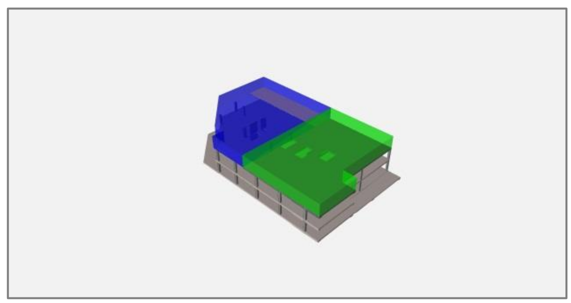
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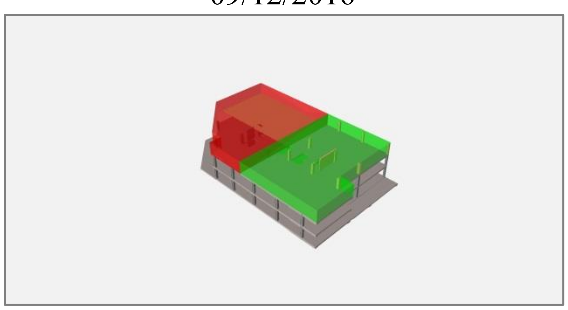
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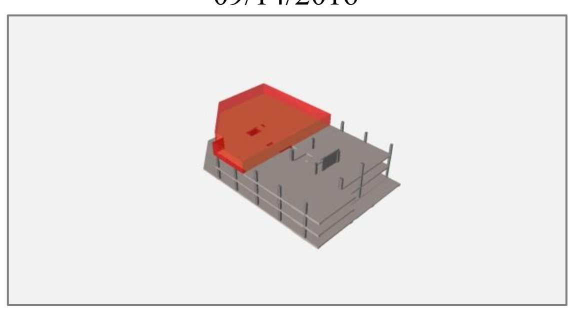
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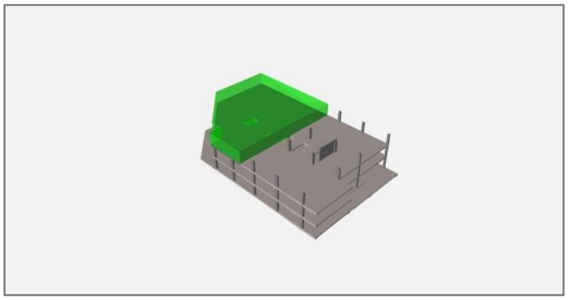

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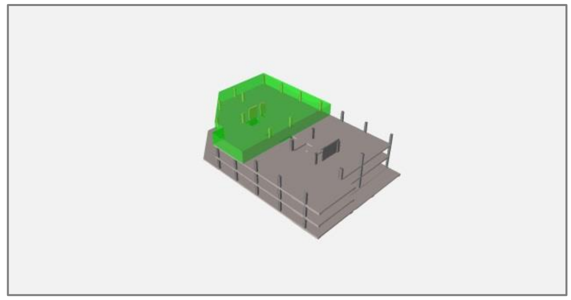

09/23/2016

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